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ACRONYMS

Acronym	Definition
ASME	American Society of Mechanical Engineers
BEA	Battelle Energy Alliance
BMW	Bi-metallic Weld
CCS	Core Conditioning System
COP	Core Outlet Pipe
CIP	Core Inlet Pipe
CUD	Core Unloading Device
DBA	Design Basis Accident
DDN	Design Data Needs
DPP	Demonstration Power Plant
FEA	Finite Element Analysis
FHSS	Fuel Handling and Storage System
FOAKE	First-of-a-Kind Engineering
GS	Grain Size
HPB	Helium Pressure Boundary
HPS	Hydrogen Production System
HRB	Hochtemperatur Reaktorbau (High Temperature Reactor Builders)
HSS	Helium Services System
HTGR	High Temperature Gas-Cooled Reactor
HTIV	High Temperature Isolation Valve
HTR	High Temperature Reactor (Germany)
HTR-10	10MWt High Temperature Test Reactor (Chinese)
HTS	Heat Transport System
HTTR	30MWt High Temperature Test Reactor (Japanese)
HX	Heat Exchanger
IHX	Intermediate Heat Exchanger
INL	Idaho National Laboratory
JAEA	Japan Atomic Energy Agency
KVK	Komponentenversuchskreislauf (Component Test Facility)
KWU	Kraftwerk Union (incorporated into AREVA)
LCF	Low Cycle Fatigue

Acronym	Definition
LWR	Light Water (Nuclear) Reactor
MHTGR-SC	Steam Cycle Modular HTGR
MIT	Massachusetts Institute of Technology
NGNP	Next Generation Nuclear Plant
NHSB	Nuclear Heat Supply Building
ORNL	Oak Ridge National Laboratory
PBMR	Pebble Bed Modular Reactor
PCDR	Preconceptual Design Report
PCHE	Printed Circuit Heat Exchanger
PCHX	Process Coupling Heat Exchanger
PCS	Power Conversion System
PFHE	Plate-Fin Heat Exchanger
PHTS	Primary Heat Transport System
PNP	German HTR development program for coal conversion applications
R&D	Research and Development
RIT	Reactor Inlet Temperature
ROT	Reactor Outlet Temperature
RPV	Reactor Pressure Vessel
SG	Steam Generator
SHTS	Secondary Heat Transport System
SSCs	Systems, Structures, Components
VHTR	Very High Temperature Gas-Cooled Reactor

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Appendix 1: BRAZING CONSIDERATIONS AND LITERATURE SURVEY **1**

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Appendix 3: 50% REVIEW VIEWGRAPHS **1**

Appendix 4: 90% REVIEW VIEWGRAPHS **1**

SUMMARY AND CONCLUSIONS

The Intermediate Heat Exchanger (IHX) and Heat Transport System (HTS) Conceptual Design Study has made a significant contribution to the advancement of the PBMR NGNP design. In particular, the study has provided enhanced insights into some of the more difficult issues pertaining to the HTS and its major components, especially the IHX.

The overall results of the IHX and HTS Study are summarized in the following sections, respectively addressing IHX design alternatives, IHX materials, HTS layout options and HTS technology development. Conclusions deriving from these results are given at the end of this summary, along with recommendations for further work.

IHX Design Alternatives

As requested by the BEA work statement, the assessment of IHX design alternatives began with an expansion of the initial survey of IHX alternatives that was included in Reference 1. In addition to the shell and tube and compact IHX options that were previously evaluated, the expanded survey included the Capillary Heat Exchanger, a small-diameter tube shell-and-tube heat exchanger proposed by UC Berkeley. The expanded survey also addressed additional attributes against which the heat exchangers were evaluated. The expanded IHX survey essentially confirmed the initial conclusions documented in the PCDR, specifically:

- A compact heat exchanger design is required for the IHX in order to meet NGNP economic goals
- Both plate (PCHE) and plate-fin (PFHE) heat exchangers are potentially viable candidates

It was further concluded that no incentives are seen for small-diameter tube shell-and-tube heat exchangers, relative to the compact PCHE and PFHE designs.

In parallel with the expanded assessment of design alternatives, reference IHX functions and requirements were developed as a basis for the present study. These functions and requirements were derived from those that served as the basis for the initial PCDR design. One significant modification was made, a reversal of the normal operating pressure bias, such that the SHTS is maintained at a slightly higher pressure than the PHTS. This was done to avoid contamination of the SHTS in the event of small IHX heat transfer pressure boundary leaks. It should be noted that the modifications to the functions and requirements were developed solely for the purposes of this study, and must be confirmed for broader use through a structured conceptual design process that takes into account other factors beyond the scope of the study.

Based upon the modified functions and requirements, initial reference HTS concepts were developed for both core-side (P1) and shell-side (S3) coupling to the IHX (Figure 1). Since the present study was to focus on plate-fin IHX technology, core-side coupling of the PHTS was selected as the initial basis for the IHX design work to follow. This is the reverse of the PCDR configuration, which was based upon shell-side coupling to the PHTS; however, along with the SHTS to PHTS pressure bias, it places the heat transfer cores of the IHX in compression during normal operation (potentially significant for the PFHE but not for the PCHE). Both the coupling option and the direction of pressure bias were further evaluated later in the study.

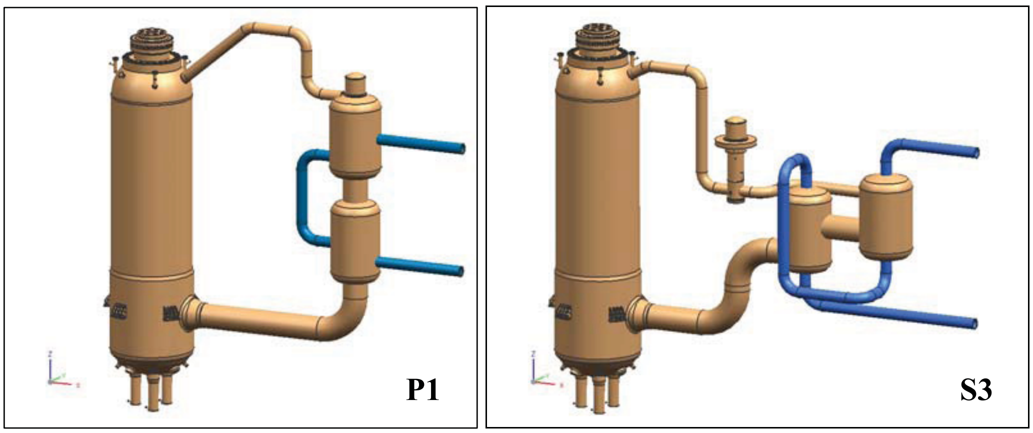


Figure 1 Core-Side and Shell-Side PHTS Coupling Options

Both the PFHE and PCHE are viewed as potentially viable IHX candidates. This study only focused on the PFHE. Three full-sized (510 MWt) PFHE designs were developed and evaluated for the single-loop application in response to the functions and requirements. In addition, a second small-diameter tube shell-and-tube heat exchanger, designated the "Involute Heat Exchanger", was developed and evaluated. As a result of these evaluations, Options C, one of the three PFHE designs, was selected as the basis for further work. Options C is shown in Figure 2.

A key feature of Option C is the individual pipes that connect the heat transfer core modules to the central ducts at the top and bottom of the heat exchanger. In addition to providing flexibility for thermal response, this feature offers the potential for module-level location and isolation of leaks across the PHTS to SHTS pressure boundary.

In addition to the 510 MWt IHX for single-loop applications, reduced scale PFHE IHX designs were developed for two-loop (2 x 255MWt) and multi-parallel (18 x 28.3MWt) architectures, as input to later HTS evaluations.

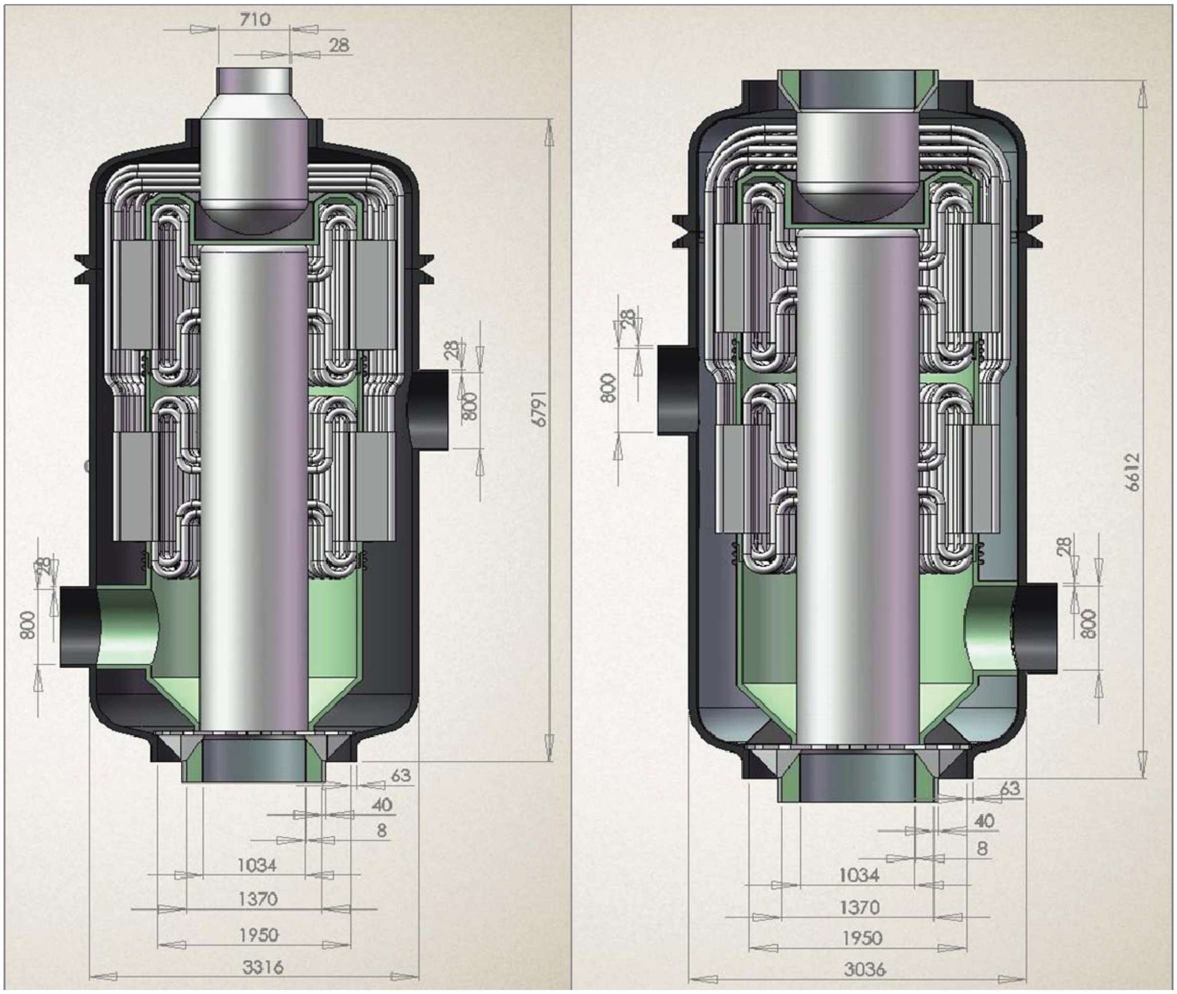


Figure 2 IHX Option C

IHX Materials

In the course of pre-conceptual design, metallic materials were identified as a key technical challenge at the specified reactor outlet temperature of 950°C. This led to a decision to separate the IHX into two sections in series, a high-temperature section, designated IHX-A, and a lower-temperature section, designated IHX-B. During the present study, the issues pertaining to metallic materials were further addressed.

A review of the prior PCDR materials evaluation, supplemented by an expanded survey of available data, concluded that the high-temperature characteristics of Alloy 617 are superior to those of Alloy 230 in the range of interest. It was further confirmed that the database supporting Alloy 617 is more complete. Accordingly, Alloy 617 is recommended as the basis for the high-temperature section of the IHX, IHX-A. The PCDR selection of Alloy 800H was confirmed as the material selection for the lower temperature, IHX-B, section.

Materials-related lifetime limitations in the high-temperature IHX-A section were evaluated from the perspectives of both strength and environmental influences. To support this evaluation, normal operating conditions, plus two simplified transients, were specified in the functions and requirements.

The evaluation against normal operating conditions, specifically the SHTS to PHTS pressure bias at 950°C, indicated that the lifetime of the heat transfer core matrix of the PFHE is not creep-limited, as initially expected. This was found to be true for both external (study reference with SHTS to PHTS pressure biasing and core-side coupling to the PHTS) and internal pressure biasing of the core matrix.

The first of the two evaluated transients was startup and shutdown, a high-frequency normal operating transient that involves the largest temperature change in the transition from one state to the other. The potential concern with this transient would be the possibility of high-temperature low-cycle fatigue. Results of the analysis indicated that the startup/shutdown transient does not significantly influence the life of IHX-A.

The second evaluated transient was loss-of-secondary-pressure (LOSP), a low-frequency design basis event (DBE). In the absence of detail system-level transients, the definition of the LOSP transient was simplified to assume an instantaneous loss of secondary pressure whilst stopping the PHTS blower. This definition is more consistent with a so-called beyond design basis event (BDBE) large pipe break. This conservative definition serves to envelope the worst case possible LOSP transient. With internal pressurization (the study reference, based on core side coupling to the PHTS), scoping analyses of the core-matrix only indicated that over 300 hours would be available prior to creep-rupture to rebalance the pressure differential across the PHTS/SHTS boundary. However, additional design and analysis will be required to confirm this result for the heat exchanger as a whole, particularly at the edges of the heat exchanger and in the manifold area. With shell-side coupling to the PHTS, the LOSP event would result in external pressure, and rupture of the pressure boundary would be unlikely.

Environmental effects, notably the potential for "corrosion" resulting from small levels of impurities in the high-temperature helium of the PHTS and SHTS, were a particular focus of the present study. The concern with corrosion is amplified due to the thin cross-sections associated with both the PCHE and PFHE compact heat exchangers proposed for use in the IHX application. The results of the environmental assessment suggest that corrosion effects are potentially life limiting for IHX A at 950°C. It was further concluded that, while the indications are troubling, adequate data do not exist to assess the potential for corrosion of Alloy 617 in thin sections. Obtaining the data necessary to definitively evaluate these effects should be given high priority in the ongoing NGNP technology development program.

Finally, it was noted that Hastelloy XR, which was used for the Japanese HTTR IHX design, has greater resistance to corrosion in the HTGR helium environment than Alloy 617; however its strength at 950°C is inferior. If a lower reactor outlet temperature were to be considered for the NGNP, further consideration should be given to this material.

HTS Options

In addition to the IHX, further evaluations of the circulator and steam generator, plus the need for isolation valves were undertaken as input to system-level considerations of the HTS as a whole. A particular objective of this study was to evaluate the trade-offs of one- versus two-loop HTS configurations.

Circulator

Contrary to initial plans, it was not possible to obtain the support of a circulator vendor due to the short timeframe allocated for the study. However, at the reactor inlet temperature selected for the PBMR NGNP (350°C), the circulator design and manufacture is not viewed as being a feasibility issue. Internal assessments indicate that the circulator design will not have a significant bearing on establishing the number of HTS loops.

Isolation Valves

Functions and requirements that might lead to the selection of isolation valves in the PHTS and/or SHTS were evaluated as part of the present study. The potential sources of requirements that were considered included normal operation, including planned maintenance, investment protection and safety and licensing, including application of ASME code requirements. It was noted in the evaluation that isolation valves are already provided in the Power Conversion System (PCS) (to limit water/steam ingress into the SHTS in the event of tube failure) and in the Hydrogen Production System (HPS) to mitigate Process Coupling Heat Exchanger (PCHX) failures. Further, overpressure protection is provided in the form of relief valves in both the PHTS and SHTS.

Assuming that PHTS/SHTS pressure boundary integrity can be maintained within the IHX under LOSP conditions, no functions and requirements were identified that would indicate the need for active PHTS or SHTS isolation valves to mitigate operational events. There are potential requirements for isolation of PHTS components for maintenance purposes when the plant is shut down and the PHTS and SHTS are depressurized.

Independent of the functions and requirements assessment, summarized above, a review of the current development status of isolation valves was undertaken in response to the BEA workscope. Two examples were found of valves that have been designed and tested. The first is a 204 mm Japanese valve that was developed for the HTTR. The second is a 700 mm valve that was developed in Germany in support of the Process Nuclear Heat (PNP) plant design in the 1980s timeframe. While demonstrated temperatures are comparable, both the size and differential pressure are below those of the PBMR NGNP design. If a need were identified for such designs, both would require additional development and qualification testing. In addition to the Japanese and German valves, which are designed to be actuated in response to operational events, a third valve design was identified that is intended to support maintenance activities, while the plant is shut down at low pressure. This latter valve has undergone design only, and has not yet been fabricated or tested.

Steam Generator

An assessment of the PBMR NGNP steam generator was undertaken by Doosan Heavy Industries and Construction, an established manufacture of steam generators for the LWR industry. The assessment addressed a range of issues, including manufacturability, development needs, economics, risk, schedule, plus operations and maintenance. The principal focus was trade-offs between one large steam generator (520MWt) and two smaller parallel steam generators (260MWt).

The study concluded that, for the larger steam generator, there is increased, but acceptable, challenge and risk with respect to manufacturing, and that more development would be required, mainly due to the larger number of tube columns and larger diameter of the tube bundle. However, both steam generators were considered to be within the current technology base. The cost of the larger steam generator is estimated to be some 30% lower than for two of the smaller 260 MWt steam generators. This assumes that shipping costs from the port of entry to the U.S. site are comparable and, implicitly, that on-site assembly would not be required for either unit. No significant differences were found with respect to other factors. On balance, the lower cost of the larger steam generator is seen as outweighing the other minor differences that were noted; however, inland transportability remains to be evaluated.

Options for Coupling of the IHX to the PHTS and SHTS

With the benefit of the component-related inputs, summarized above, options for coupling the IHX to the PHTS and SHTS were further assessed in conjunction with the direction of pressure biasing during normal operation. Heat exchanger-specific differences were identified, where applicable. The most important considerations were found to include the arrangement and support of the HTS components within the Nuclear Heat Supply System building, the direction of pressure biasing during normal operation and for the LOSP event (the latter being specific to the PFHE), access for inspection and maintenance of the IHX and the related issue of the overall maintenance philosophy.

Overall, it was concluded that the scope of the present study did not provide the basis for a definitive selection of the P1 (core-side coupling to the PHTS) or S3 (shell-side coupling to the PHTS) options. As suggested above, the differences to be evaluated involve other systems, structures and components, plus plant-level assessments that were beyond the scope of the present study and more appropriate to an integrated Conceptual Design phase. In the interim, PBMR recommends the retention of IHX coupling Option P1 and SHTS to PHTS pressure biasing during normal operation as the basis for related conceptual design studies (e.g., Contamination Control).

HTS Layout Evaluation

Taking into account all of the above, a comparison was made of three HTS layout options:

- A single-loop HTS with a single 510 MWt IHX and a single 520 MWt SG
- A two-Loop HTS with two 255 MWt IHXs and two 260 MWt SGs
- A single-Loop HTS with 18 parallel IHXs and a single 520 MWt SG

The comparison was first undertaken from the component perspective, taking into account the perspectives of the reactor, piping, IHX, circulator, SG and PCHX. In general, a single loop configuration is preferred from the component viewpoint. However, a two-loop configuration would be also acceptable. The option of a single loop with multiple parallel-coupled IHXs was viewed as being not preferred from the piping and IHX viewpoints, due to complexity and cost.

A Kepner-Tregoe analysis was used to evaluate trade-offs from the overall system perspective, taking into account the categories of design development, manufacturing and transportability, operation and maintenance, safety and investment protection, and lifecycle cost. The Kepner-Tregoe analysis also indicated a preference for the single-loop HTS configuration. Key advantages of the single-loop HTS were related to lower capital cost and system simplicity, the latter also implying improved reliability. These advantages were seen as more than offsetting modest increases in design and development costs and risks associated with the single-loop option.

As a conclusion of the analysis, it is recommended to remain with a single-loop HTS, with a single IHX (with A and B sections), as the reference PBMR NGNP HTS design, pending new insights from future conceptual design activities.

HTS Technology Development

With the additional insights obtained through this study, the Design Data Needs (DDNs), initially developed as part of the PBMR NGNP Preconceptual Design, were updated. Significant changes were made, primarily in the materials-related areas. Specifically, with the identification of Alloy 617 as the reference material for IHX-A, previously identified DDNs for Alloy 230 were deleted. Supplemental DDNs were identified to complete the qualification of Alloy 800H, which was confirmed as the reference material for IHX-B. Additional DDNs were developed to address corrosion-related issues identified through the IHX materials assessment, plus issues related to diffusion bonding and brazing.

Conclusions

The overall conclusions of the IHX and HTS Conceptual Design Study are summarized as follows:

1. The PCDR recommendation to utilize PCHE or PFHE compact heat exchanger technology as the basis for the IHX design has been confirmed through the present study.
2. A compact IHX configuration (applicable to both PCHE and PFHE heat exchangers) has been identified that potentially allows leak detection, location and isolation at the module-level.
3. Due to potential life limitations associated with high-temperature corrosion, the acceptability of a compact metallic IHX at 950°C remains to be confirmed. The present database for thin section materials is inadequate to support a definitive assessment.
4. The PCDR recommendation to separate the IHX into IHX-A and IHX-B sections, based on temperature, is supported by the results of the present study.
5. The PCDR recommendation to undertake a parallel development of ceramic HX technology for IHX A is confirmed by the present study.
6. The selection of core-side or shell-side coupling of the IHX to the PHTS requires additional system- and component-level information that is beyond the scope of the present study.
7. A single-loop HTS configuration is preferred, based both on component and system level considerations.

Recommendations

The following recommendations are provided for future work:

1. Update the plant-level Functions & Requirements.

   It is particularly important that the NGNP mission be confirmed or redefined, along with the associated overall plant performance requirements. Especially important is the ultimate goal for the reactor outlet temperature (presently 950°C). It is noted that the present PBMR NGNP Preconceptual Design offers the flexibility to initially operate as an indirect steam-cycle or lower temperature process heat plant and then to evolve to higher temperatures.

2. Advance the overall NGNP Nuclear Heat Supply System (NHSS) integrated conceptual design, to better focus development of individual systems and components, including:
   - Undertake a conceptual design study to develop and/or verify the combinations of insulation and active cooling provisions for the HTS.
     - A particular focus is assessing the feasibility of passive insulation for the SHTS and also its potential for the PHTS.
   - Develop HTS analytical models for the NHSS at a level sufficient to provide thermal/structural input to component designs, notably the IHX
     - Component conceptual designs (IHX, Blower, SG, PCHX etc) needed as input to HTS analytical models e.g., blower maps, mass of metal, etc. (iterative process).
   - With support of the respective vendors, develop the conceptual designs of the PCHE and PFHE to a level at which structural adequacy is established for normal operation and DBEs, notably including the LOSP event. Scope to include:

- Iterative design and structural analyses
- Develop an IHX maintenance philosophy and conceptual approach for inspection and maintenance that, as a minimum, includes consideration of:
  - Plant level availability and maintenance strategy/philosophy
  - The implications of leaks between the PHTS and SHTS as a function of the direction of pressure bias
  - The feasibility of heat transfer (HT) module isolation by plugging of lead-in/lead-out tubes
  - Heat transfer module isolation vs. IHX replacement
  - PHTS and SHTS helium purification system requirements/capabilities
- Further develop the IHX/HTS coupling trade-offs (P1 vs. S3 vs. other) as input to overall system-level plant layout.
- Support the development of detailed technology plans to address corrosion in thin metallic IHX sections and other high-priority DDNs (see Item 3, below)

- With the support of a vendor, develop reference circulator concepts for the PHTS and SHTS.
- With the support of a vendor, advance the reference SG design for the PCS.
- Develop a plant-level maintenance strategy/philosophy as input to component maintenance.
- Based on the above, optimize/propose a system-level layout following system-level and component design trade-offs.
- Develop FOAK and NOAK cost estimates for major HTS components

3. Develop and implement detailed technology development plans to address high-priority DDNs, notably including (in priority order):
   - HTS-01-21 and HTS-01-29, Corrosion Allowances for Alloy 617 and Alloy 800H in thin sections
     - As necessary, develop detailed design/specifications for a corrosion test facility
     - Provide sufficient information (F&Rs, designs, cost, schedule, etc.) to allow a decision to proceed with development of the test facility and the conduct of testing.
   - HTS-01-30, Brazing and Diffusion Bonding Processes for Alloy 617 and Alloy 800H
   - HTS-01-18 and HTS-01-19, Data Supporting Materials and Design Code Cases
   - HTS-01-03 and HTS-01-24, Properties of Joints
   - Complete the design and initiate the construction of a heat transfer test facility to support confirmatory IHX performance and integrity tests at the module level (HTS-01-17)

4. Establish a parallel effort to design and develop ceramic heat exchangers, as outlined in the PCDR.

References

1. *NGNP and Hydrogen Production Preconceptual Design Report, NGNP-ESR-RPT-001, Revision 1, Westinghouse Electric Company LLC, June 2007.*

INTRODUCTION

This report documents the results of the Intermediate Heat Exchanger (IHX) and Heat Transport System (HTS) Conceptual Design Study. The objectives of the study and the organization of this report are summarized below.

Objectives and Scope

The overall objective of the IHX and HTS Conceptual Design Study was to advance the designs of the PBMR NGNP Intermediate Heat Exchanger IHX and the overall Heat Transport System. Corollary objectives are summarized as follows:

- Update and expand the survey of candidate heat exchangers that are prospective candidates for the IHX application
- Evaluate Plate-Fin Heat Exchanger (PFHE) technology for the IHX application
- Advance the design of the IHX with particular emphasis on IHX/HTS integration
- Address technical issues identified in the PCDR, particularly those that limit IHX lifetime, and evaluate their sensitivity to temperature
- Update and expand the assessment of IHX metallic materials
- Advance the understanding of other key HTS components, including the circulator and steam generator
- Evaluate the need for secondary HTS (SHTS) isolation valves and characterize their present state of development
- Evaluate the trade-offs between one- and two-loop HTS architectures and the prospects for multiple parallel IHX arrangements

The above objectives were achieved in the course of the study and the results are documented in this report.

Organization of the Report

The IHX and HTS Conceptual Design Study Report is organized within five sections that follow this introduction. Section 1 focuses on the design of the IHX itself. It begins by updating the initial survey of candidate heat exchangers and adds an evaluation of a small-diameter-tube shell-and-tube heat exchanger known as the “Capillary Tube” heat exchanger. The section continues with the identification of functions and requirements that serve as a basis for the design work that follows. Two heat exchanger designs, the PFHE and Involute concepts, are then developed and evaluated, with the former being selected as the basis for the remainder of the report.

Section 2 addresses IHX materials. It begins with an update of the PCDR material survey, followed by a detailed evaluation of materials limitations that may tend to limit the lifetime of the high temperature section of the IHX. The sensitivity to temperatures also addressed.

Section 3 addresses aspects of the HTS. It begins with consideration of Steam Generator trade-offs related to its size and is followed by an assessment of the need for SHTS isolation valves. Trade-offs associated with options for coupling the IHX to the PHTS and SHTS are then addressed. The section concludes with an assessment of one-loop, two-loop and multiple parallel IHX architectures.

Based upon the preceding sections, Section 4 identifies changes to the Design Data Needs (DDNs) documented in the PCDR that are indicated by the results of the present study. Updated DDNs are provided as an appendix.

The report concludes with Section 5, which summarizes the overall conclusions of the report and provides recommendations for follow-on work.

1 IHX DESIGN ALTERNATIVES

1.1 Survey of Present IHX Designs

A high-level qualitative evaluation of IHX design alternatives was developed and documented in Section 20.3.3.5, "IHX Design Considerations" and Table 20.3.3-1, "Summary of Design Tradeoffs for Evaluated HX Types", of the WEC Preconceptual Design Heat Transport System Special Study (Ref. 1-1). In this section, the qualitative evaluation of Reference 1-1 is expanded in scope and extended to include small-diameter tube heat exchangers, as represented by the "Capillary Tube and Shell Heat Exchanger", described in Reference 1-2. A second small-diameter tube heat exchanger, the "Involute Heat Exchanger" is described in Section 1.5 of this report, and evaluated in Section 1.6.

With the exception of the Capillary Tube and Shell Heat Exchanger, descriptions of the heat exchangers addressed in this survey are provided in Reference 1-1 and are not repeated here. The basic concept of the Capillary Tube and Shell Heat Exchanger is shown in Figure 1-1, which is taken from Reference 1-2. Design parameters for a 50MWt gas-to-liquid salt version of the heat exchanger are provided in Table 1-1, also from Reference 1-2. Features worthy of note include the very large number of very small tubes, and the novel approach to constructing the tubesheets from the tapered ends of the tubes themselves. While comparable details are not provided for a He-to-He heat exchanger, the total weight is estimated in the paper to increase from 30,000 kg to 44,000 kg and it is noted that the heat exchanger would be operated in a pressure-balanced condition.

The results of the present assessment are summarized in Table 1-2. The survey is conducted in the framework of seven categories that are described and evaluated in the subsections that follow.

1.1.1 Cost/Performance Indicators

Three cost/performance indicators are included. The first is compactness, which can be measured in terms of heat transfer surface density (m^2/m^3) or, alternatively, heat transfer density (MW/m^3). Both relate to the ability to develop practical heat exchangers with high effectiveness and to enclose those heat exchangers in vessels of reasonable size. Traditional shell-and-tube heat exchangers tend to have poor compactness relative to advanced designs, and particularly in gas-to-gas heat exchange applications. While the HTTR helical coil heat exchanger concept is cited as a typical example, helical coil configurations may not be optimal for large gas-to -gas exchangers and straight-tube variants could also be considered. Heat exchangers with small diameter tubes, such as the Capillary Shell and Tube concept, offer improved compactness, largely as a result of the reduced hydraulic diameters and improved heat transfer coefficients on the tube-sides of these heat exchangers. Both the PCHE and plate-fin exchangers offer a high degree of compactness.

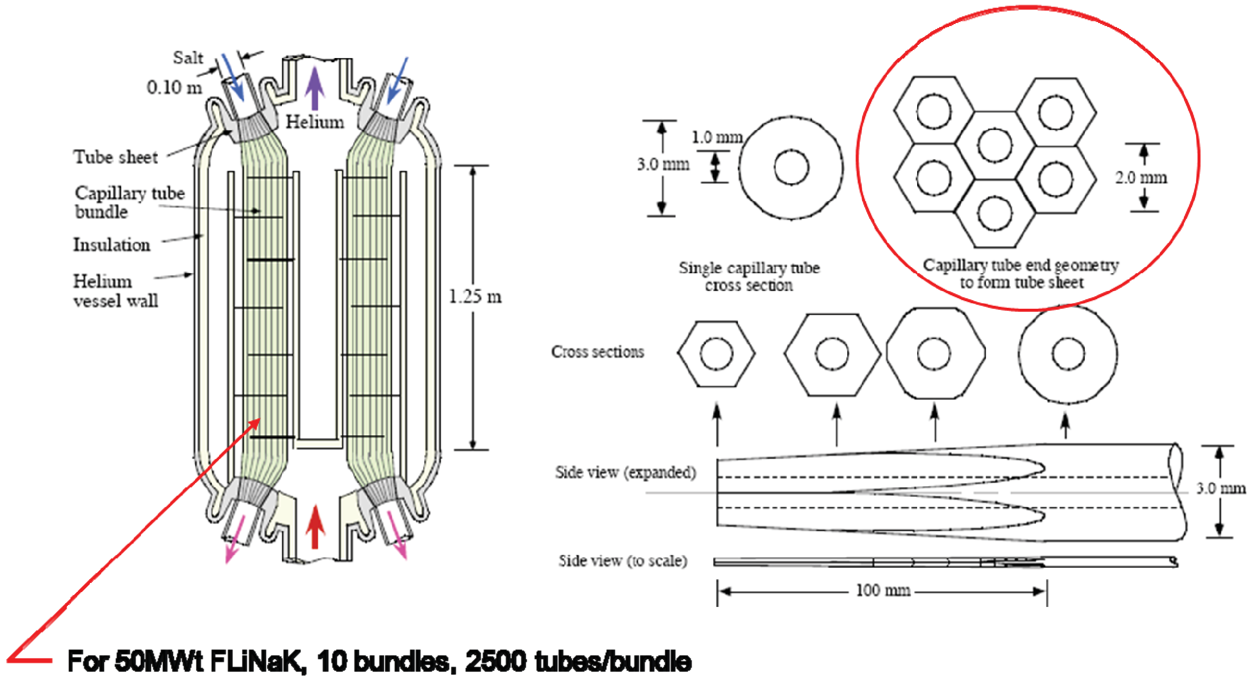


Figure 1-1 Capillary Tube and Shell Heat Exchanger

Table 1-1 Capillary Heat Exchanger Non-Optimized Reference Design Parameters

Total thermal power	50 MW(t)
Flinak inlet/outlet temperatures	565°C / 925°C
Flinak total mass flow rate	73.718 kg/sec
Helium inlet/outlet temperatures	950°C / 590°C
Capillary tube inner/outer diameters	1.0 mm / 3.0 mm
Heated/total tube length	1.8 m / 2.0 m
Total number of tubes	259,000
Number of tubes in one 10-cm diameter tube sheet bundle	2,500
Total number of tube bundles	104
Flinak pressure drop	810 kPa
Flinak pumping power	430 kW

Table 1-2 Qualitative Comparison of Heat Exchanger Concepts

Metric	Shell & Tube	Capillary Tube	PCHE	Plate-Fin & Prime Surface
Assumed Design	Helical Coil (e.g., HTTR)	University of CA Berkeley	Heatric DPP Recuperator	Brayton Energy Unit Cell
Cost/Performance Indicators				
Compactness (m^2/m^3 & MW/m^3)	Poor	Intermediate	Good	Good
Materials Utilization (t/MWt)	Poor: (13.5 t/MWt) Unlikely to be commercially viable	Good (0.9 t/MWt)	Good: (estimated to be 1.2 to 1.5 times plate-fin in final form; needs confirmation)	Best: (0.25 t/MWt) Most compact, least materials
Manufacturing Cost	Established manufacturing process	Manufacturing process looks to be very labor intensive and expensive.	Established manufacturing process, amenable to volume manufacturing	Established manufacturing process, amenable to volume manufacturing
State-of-the-Art				
Experience Base	HTTR, German PNP Development	None	PBMR DPP Recuperator, other commercial products	Conventional GT recuperators
Design & Manufacturing	Proven designs and manufacturing processes.	Proposed tubesheet manufacturing process not obviously feasible. Shell-side baffling will be very difficult with very large numbers of very small tubes	Proven designs and manufacturing processes.	Proven designs and manufacturing processes.
Robustness				
Normal operation	Best: Simple cylindrical geometry, stresses minimized in HT area. Header interfaces can be easily isolated from HT area.	Simple geometery of tubes a plus. Temperature effects on "tubesheet" unknown.	Good: Thicker plates; local debonding does not immediately affect pressure boundary.	Concern: Thin plates with brazed joints in pressure boundary; stress risers in pressure boundary joints (but normally operate in compession). Small material and braze defects more significant.
Transients	Good: Simple cylindrical geometry avoids stress concentrations in HT area. Potential issues in headers, tube/header interfaces.	"Tubesheet" and tube/tubesheet interfaces are potentially problematical	Differing thermal response characteristics of inner HT core vs. solid outer boundary surrounding HT core raises potential for higher transient thermal stresses vs. plate-in.	Best: Thin sections and flexible design minimizes the effects of transients.
Environmental Compatibility				
Coolant chemistry/ corrosion effects (Assumes PHTS on tube side or inside of compact HX cells, SHTS on shell/outside)	Best: Thick tubes provide maximum resistance	Favorable tube-side geometry. Intermediate section thickness and susceptibility to corrosion effects.	Intermediate section thickness and susceptibility to corrosion effects. Potential greater for "hideout" effects than tubular designs.	Worst: Thin plates and fins, potentially aggrevated by "hideout" locations, may be more susceptible to coolant chemistry effects.
Dust, erosion (Assumes PHTS on tube side or inside of compact HX cells, SHTS on shell/outside)	Best: Large tube IDs, thick tubes make dust/erosion an non-issue.	Intermediate: Will be more prone to dust collection due to smaller diameters, but low likelihood of direct impingement	More prone to dust deposition and erosion (small passages, potentially with features to enhance HT). PCHE cross-sections are thicker than plate-fin/prime surface.	More prone to dust deposition and erosion (small passages, with features to enhance HT). Fin cross-sections are thinner than PCHE cross-sections.
Tritium transport	Best: Thick tubes provide maximum resistance.	Intermediate. Thinner tubes	Worse. Average PCHE cross-sections thicker, but minimum cross-sections comparable to plate-fin/prime surface.	Worst: Thin plates provide least resistance to tritium transport.

Table 1-2 Qualitative Comparison of Heat Exchanger Concepts (Cont'd)

Metric	Shell & Tube	Capillary Tube	PCHE	Plate-Fin & Prime Surface
Assumed Design	Helical Coil (e.g., HTTR)	University of CA Berkeley	Heatric DPP Recuperator	Brayton Energy Unit Cell
Reliability & Integrity Management (RIM)				
Detection of degradation and/or leaks during operation (Assumed SHTS to PHTS pressure bias)	Equivalent. Essentially pressure balanced during normal operation with SHTS at slightly higher pressure. Indication of significant leakage would be manifested as inability to maintain higher SHTS pressure and/or increased injection of SHTS helium and increased withdrawal of PHTS helium.			
Detection of degradation and/or leaks during outages	Large tube diameters may allow internal inspection of individual tubes to assess condition.	Design allows access to individual tubes to identify presence of leaks. However, a lot of tubes	Leaks can be detected at module level with concept similar to that proposed for plate-fin	Concept developed to detect leaks at module level.
Leak location; isolation, repair or replacement of failed components	Design allows location of leaks in individual tubes and plugging.	Design allows location of leaks in individual tubes and plugging. However, a lot of tubes.	Leaks can be isolated at module level with concept similar to that proposed for plate-fin.	Concept developed to locate and isolate leaks at module level.
HX Integration				
Integration with Vessels & Piping	Headers and HX-vessel integration demonstrated (e.g., HTTR, German PNP)	Integration with piping needs further evaluation	OK (by inference from plate-fin work).	OK
Compatibility with Multi-Stage IHX Designs	Large vessels tend to make less attractive	High manufacturing costs would make less attractive.	Compatible with multi-stage designs.	Compatible with multi-stage designs.
Compatibility with Multi-Module IHX Designs	Large tubes, headers likely incompatible with multi-module designs.	High manufacturing costs would make less attractive.	Compact cores are good match with multi-module designs.	Very compact cores are best match with multi-module designs.
Compatibility with Alternate HT Fluids (PHTS to SHTS)	Poor tube-side HT characteristics problematical for alternate gases with lower conductivity. Potentially best choice for LS designs with LS on tube side (drainable). Headers would be an issue for high-temperature outlet.	Poor tube-side HT characteristics problematical for alternate gases with lower conductivity. May be OK for LS designs with LS on tube side (drainable). Tubesheets would be an issue for high-temperature outlet.	Design provides flexibility for matching characteristics of differing HT fluids, including LS. May be difficult to develop drainable design for LS.	Likely not compatible with liquid salt HT fluids. Good flexibility for matching HT characteristics of alternate gases.
Design/Licensing Basis				
Code Basis for Design	Existing Sect VIII Code design basis for tubular geometries and likely header designs	Existing Section VIII Code design basis for tubes, but header design has no Code precedents.	No existing design Code basis	No existing design Code basis

The second indicator is a measure of the material requirements per unit of heat transfer (MW/t). This relates to the efficient use of the very expensive materials that are typical of high temperature heat exchangers, such as the NGNP IHX. Again, the shell-and-tube heat exchanger is relatively inefficient in terms of materials usage. The small-tube heat exchangers offer an approximately 10-fold improvement, again largely based upon their improved tube-side heat transfer characteristics. The plate-fin heat exchanger offers the best materials utilization, with a further 4-fold improvement relative to the small-tube designs. The materials utilization of the PCHE is estimated to be 1.2 to 1.5 times greater than the plate-fin heat exchanger in its as-manufactured form.

The third indicator relates to the difficulty of the manufacturing process and corresponding cost implications. The manufacturing process for shell-and-tube heat exchangers is well-established. In addition to the HTTR IHX, a number of helical coil steam generators have been constructed and operated in earlier nuclear plants, including HTGRs. The present ASME Code provides for the structures found in this class of heat exchangers, albeit at lower temperatures. A disadvantage is that the manufacturing processes for helical heat exchangers are relatively labor intensive.

There is no experience with the manufacturing techniques proposed for the Capillary Shell and Tube design, and the feasibility of assembling the tubesheets by joining together the ends of the tubes is yet to be established. The ASME Code basis for such assemblies would also need to be developed. In addition, the very large number of tubes (>250,000 for a 50MWt heat exchanger) and the implied manufacturing processes appear to indicate a very expensive structure.

There are existing commercial applications of both the PCHE and Plate-Fin heat exchanger concepts, and both are amenable to volume manufacturing techniques. Reduced manufacturing costs, along with their relatively efficient use of metal structures, suggests lower capital costs, when compared with either of the tubular options. Of the two, the reduced materials requirements would be an advantage for the Plate-Fin heat exchanger; however, a comparative study would be required to confirm an overall advantage for one or the other.

1.1.2 State-of-the-Art

Two characteristics are identified in this category. The first is the experience base for these or similar heat exchangers. The second is the degree to which the manufacturing processes required for manufacturing of the heat exchangers are presently available or, alternatively, require development. These indicators can be thought of in terms of development risk.

As already noted above, there is a significant base of experience for the large shell and tube heat exchanger and for the two compact heat exchanger designs. In the case of the shell and tube heat exchanger, such experience includes nuclear applications, including small IHXs. In terms of manufacturing experience, a number of large helical steam generators have been constructed and operated in nuclear plants (e.g., Fort St. Vrain). The design features of these steam generators are expected, in many respects, to be similar to those likely to be incorporated in large IHXs.

Both the PCHE and plate-fin heat exchangers are used in multiple conventional applications, albeit at lower temperatures. Notably, the PCHE design is being developed as the recuperator for the PBMR DPP.

For all of these “conventional” heat exchangers, the principal extrapolation relates to the high temperatures that will be seen in operation. These high temperatures lead to the need to select and qualify high-temperature materials and associated joining methods and to verify operational feasibility over the design lifetime.

By contrast, there is no experience base for the proposed capillary tube heat exchanger. The proposed tubesheet manufacturing process is not obviously feasible. Further, shell-side baffling would appear to be very difficult given the very large number of very small tubes. If feasible, this concept would require significant manufacturing development.

1.1.3 Robustness

In the context of this evaluation, "Robustness" relates to the likelihood that the heat exchanger will achieve its design service life without failure under the anticipated conditions of service. It is evaluated for both normal operating and transient conditions. It is also a measure of its evaluated tolerance to manufacturing defects. These indicators can be thought of in terms of operational risk. The conditions of service evaluated in this category refer to those creating steady state and transient stresses. Environmental issues are separately considered in the next section. For the WEC IHX application, it is assumed that the heat exchangers are operated essentially under pressure balanced conditions during all modes and states. High differential pressures would only result from rare Design Basis Events (DBEs) involving loss of SHTS pressure. It should be noted, however, that alternate HTS designs incorporating a Brayton cycle in either the PHTS or SHTS would not be consistent with this assumption.

Robustness is a particular strength of conventional shell and tube heat exchangers, and particularly the helical coil concept. In the latter, heat transfer occurs only in the tube bundle and the cylindrical tubular geometry is ideal for withstanding stresses, both during steady state and transient conditions. The relatively thick tubes also provide a degree of robustness that is not shared by the other heat exchanger concepts. While the primary inlet and secondary outlet tubesheets operate at high temperatures, their operation is essentially isothermal, thus minimizing the potential for fatigue-related damage.

The Capillary Shell and Tube heat exchanger shares some of the advantages of the helical coil concept, however the tubes are thinner and far more numerous. The structure of the tubesheet and its interface with the vessel appear problematical for this concept, particularly during transient conditions. Unlike the helical design, it would be more difficult to shield the shell-side of the tubesheet from transient conditions.

For normal operating conditions, the construction of the PCHE inner core appears to result in a relatively robust structure. The material between the heat transfer passages provides reinforcement, and any delamination of the diffusion bond between the plates would not immediately affect the PHTS/SHTS pressure boundary. On the other hand, the thermal response characteristics of the inner heat transfer core relative to the surrounding solid outer boundary (comprising the edges of the plates without flow passages) suggests a potential for transient-induced thermal stresses and fatigue that should be evaluated. The interfaces between the heat transfer core and the inlet and outlet plena are also areas of concern with respect to thermally induced stresses.

The plate-fin concept offers both advantages and disadvantages with respect to robustness. In present commercial applications, the plate-fin design has been developed for recuperated gas turbine engine applications in which transient stresses are a driving design consideration. Thus, the core design and plenum structures are designed for maximum flexibility. This offers an advantage in terms of transient response and minimizes the potential for fatigue-related failures. On the other hand, the core pressure boundary components are made up of relatively thin plates, internally supported by even thinner fins. This suggests that small material defects would potentially be more significant. Joints, including those in the PHTS/SHTS pressure boundary are brazed, and their geometry suggests that stress risers may be present which would require evaluation for designs in which the core structure is internally pressurized. While certain of these features raise concerns, the following are noted:

- For designs in which the plate-fin core structure is externally pressurized (i.e., pressure balancing is biased from the outside of the core), the brazed joints serve only a sealing function.
- As noted elsewhere in this study, the strength of brazed joints is expected to be comparable to that of the base metal.

1.1.4 Environmental Compatibility

Three indicators of environmental compatibility are addressed. The first relates to helium impurities and the corresponding potential for high-temperature corrosion. The second assesses the potential effects of circulating dust with respect to erosion and/or the possibility of plugging heat exchanger passages. The third relates to tritium transport across the heat exchange boundary from the PHTS to the SHTS.

Since the same materials are expected to be used for all of the heat exchanger options, the relative resistance to corrosion (potentially induced by trace impurities in the PHTS/SHTS working fluids) would primarily be a function of the thickness of the heat transfer surface. A secondary consideration would be “hideout” locations within the heat exchanger, where local concentrations of impurities might occur. The latter mechanism is less likely to be a significant factor in gas to gas heat exchangers, such as the IHX, than in water-based designs, such as steam generators. For these effects, the thick tube walls of the shell and tube heat exchangers would provide maximum resistance. The thin cross-sections of the plate-fin design, plus the presence of potential hideout locations, would result in greater concern for that design. The PCHE design would be of intermediate concern, noting that the thinnest sections where heat transfer channels on the PHTS and SHTS sides come closest together are comparable to those of the plate-fin design.

Some amount of graphite “dust” is expected to be present in the circulating helium of the PHTS. The extent, to which this dust becomes an issue, depends upon several factors, including:

- The amount of dust present
- The distribution of size; large particles would “drop out”, while very small particles would simply pass through the heat exchanger without adverse effect

- Local geometry and gas velocities, which would influence the likelihood of erosion or deposition

For the purposes of this evaluation, it has been assumed that the PHTS is coupled to the tube-side of tubular heat exchangers or the inside of the compact heat exchanger cells; judged to be the worst case, since the dust would be channeled directly to the heat exchange surfaces at a greater velocity.

Both the geometry and thickness of the tube walls in the shell and tube heat exchanger would tend to make that design resistant to the effects of dust. The capillary tube heat exchanger should also be resistant to erosion; however, would be more prone to deposition than the larger tubular design.

Given their small internal passages and heat transfer enhancement features, both the PCHE and plate-fin designs would be more prone to internal deposition and blockage than the shell and tube designs. In both cases, minimizing the potential for dust deposition and channel blockage may be one incentive for coupling the PHTS to the shell-side of these heat exchangers.

Since the materials of construction are common, the resistance to tritium transport from the PHTS to the SHTS will essentially vary as the thickness of the pressure boundary cross-section. In this regard, the thicker tubes of the shell and tube designs will provide greater resistance than the thin cross-sections of the compact exchangers. The significance of tritium transport is being separately evaluated.

1.1.5 Reliability and Integrity Management

Reliability and Integrity Management (RIM) is an integrated process wherein a combination of design, fabrication, inspection, surveillance, operation and maintenance requirements are established to meet reliability goals in an efficient and cost-effective manner. For the purposes of this study, the RIM evaluation is limited to heat exchanger surveillance, inspection and maintenance.

There appear to be no functional differences among the various heat exchangers with respect to the detection of heat exchanger degradation and/or leaks while the plant is operating. In all cases, materials considerations would dictate that the PHTS and SHTS pressures be essentially balanced during operation. The ability to detect leaks will vary with the direction of the PHTS/SHTS pressure bias. If the PHTS is at a slightly higher pressure, the initial indication of a leak would be the detection of radionuclides in the SHTS. Conceivably, relatively small leaks could be detected in this manner. If the SHTS is at higher pressure, small leaks may not be practically detectable in service. The indication of significantly greater leakage would first be manifested by the inability to maintain higher SHTS pressure and/or increased injection of SHTS helium and increased withdrawal of PHTS helium.

The ability to detect degradation and/or leaks during outages (in-service inspection) varies among the respective concepts. In principle, access to both ends of individual tubes is a possibility in both tubular designs. However, the large number of tubes in the capillary design raises issues of practicality. Further, methods have been proposed for inserting probes into large helically coiled tubes, conceptually allowing evaluation of tube integrity and the detection of significant degradation. The latter would not be possible with the capillary tube design. In the case of the compact heat exchanger designs, it is shown later in this study that leak detection is feasible at the module level; however, the detection of internal degradation, absent a leak, does not appear to be practical.

For similar reasons, the large shell and tube concept facilitates the location of leaks and the plugging of individual tubes. The capillary tube design offers similar potential; however, the large number of tubes implies greater difficulty. Again, as a result of this present study, compact heat exchanger design options have been identified that will allow access for the location and isolation of leaks at the module level.

1.1.6 Heat Exchanger Integration

As considered herein, heat exchanger integration relates to the relative ease or difficulty of incorporating the heat exchanger core or heat transfer surface within the vessel and with the remainder of the PHTS and SHTS piping. In the present evaluation, three additional attributes are also considered. These are compatibility with multi-stage and multi-module concepts and compatibility with alternate SHTS heat transport fluids, including other gases and liquid salt.

Integration of the heat transfer core with the vessel and HTS involves not only physical interfaces, such as internal supports and connections to inlet and outlet piping, but also vessel insulation and/or cooling. In the case of the large shell and tube designs, the integration of the heat transfer surface within the vessel has been adequately demonstrated, albeit at modest power levels (e.g., the HTTR IHX). Key features of present designs, such as the HTTR IHX, include provisions to maintain the helium pressure boundary (i.e., the vessel and outer piping) at modest temperatures by appropriate selection of flow paths, insulation and active cooling. In concept, some of the same approaches can be applied to the capillary tube heat exchanger; however, the details provided do not provide an adequate indication that this has yet been done. In particular, the interfaces between the IHX and piping need further evaluation. Integration of plate-fin designs has been a subject of the present study, and indicates that adequate integration solutions can be developed for both the plate-fin and PCHE heat exchanger options.

There is nothing that would prevent any of the IHX design options from being configured as multi-stage heat exchangers. However, two considerations in this regard are the cost of the vessels versus the heat transfer surface therein and the relative cost of integrating the heat transfer surface within the vessels. In the case of the large shell and tube designs, it is likely that multiple large parallel vessels will be required to transfer the full reactor output. Further subdividing these IHXs into high-and low-temperature sections will significantly increase cost, tending to make the multi-stage design less attractive. In the case of the capillary tube heat exchanger, the present design already implies a large number of vessels, operating in parallel. The high manufacturing costs projected for this concept would also make a multi-stage approach less attractive. The present study suggests that both the plate-fin and PCHE concepts are compatible with multi-stage IHX designs; however, whether such designs are economically optimal is yet to be confirmed.

The multi-modular concept is based upon configuring the IHX as a relatively large number of heat exchangers operating in parallel. The degree of division would be such that it is practical to replace entire heat exchangers in the event of a failure. Similar to multi-stage designs, the compact heat exchangers (PCHE and plate-fin) were found to be generally compatible with the multi-module design concept. A specific example of a multi- module plate-fin IHX is given later in this study. As with the multi-stage heat exchangers, the large sizes and high manufacturing costs of the tubular designs make them less attractive for implementation in this architecture.

The compatibility of the various heat exchanger options with alternative fluids depends upon the nature of the fluids themselves. For gaseous SHTS working fluids other than helium, the principal issue is reduced thermal conductivity, which results in larger heat transfer surface requirements. For tubular designs, this is further aggravated on the tube-side of the heat exchanger. Both the PCHE and plate-fin heat exchangers provide good flexibility for matching the heat transfer characteristics of alternate gases.

With liquid salt working fluids, the mismatch in heat transport properties is even more severe. In this case, the PCHE design appears to provide the best flexibility for matching the heat transport properties of the PHTS and SHTS working fluids. However, developing a drainable design, a requirement for liquid salt systems, may be difficult. The capillary tube concept may provide an acceptable basis for liquid salt heat exchange applications, and the tube-side should be easily drainable. The tubesheet at the high-temperature outlet of the capillary heat exchanger would be one area of concern. Due to their large tube diameters, conventional shell and tube heat exchangers would be less attractive for liquid salt applications. In general, the plate-fin concept does not appear to be compatible with liquid salt SHTS working fluids, since there is less flexibility for tailoring the flow channels to match the differing heat transfer characteristics of the gas and liquid salt fluids.

1.1.7 Design/Licensing Basis

The extent to which an established design and/or licensing basis is available within the existing codes and standards infrastructure varies from concept to concept. In general, there is no complete codes and standards basis for any of the proposed concepts at the temperatures in question. The greatest compatibility with current codes and standards rests with the conventional shell and tube design. For this design, Sections III and VIII of the ASME Code incorporate all of the required design features. Furthermore, the provisions of Section XI can likely be implemented in service. The principal deficiencies relate to the lack of materials coverage, particularly at the high temperatures proposed for the NGNP IHX. To a lesser extent, design features of the capillary tube heat exchanger are also addressed in the current code infrastructure.

A specific issue with the capillary tube heat exchanger concept is the design and fabrication of the tubesheets, which are proposed to be assembled by joining the edges of the individual tubes.

The compact heat exchangers also pose significant challenges with respect to the development of an acceptable codes and standards infrastructure. At the present time, there is no existing design code basis for such exchangers.

1.1.8 Conclusions

In summary, there are no findings from this survey that would contradict the findings of the prior Heat Transport System Special Study, conducted in support of the NGNP Preconceptual Design (Ref. 1-1). It is concluded that the development of the IHX should center upon compact heat exchanger designs. As previously noted in Reference 1-1, the PCHE is evaluated to be the more robust design; however, the plate-fin design is evaluated to offer savings in terms of material usage. Additional incentives may accrue where transient response is viewed as a significant factor. As noted later in this report, concern with the reliability of brazed joints has been somewhat mitigated as a result of additional information that has been obtained during this study.

We further conclude that there is little incentive for implementing the capillary tube concept in gas-to-gas IHX applications. However, further consideration may be merited for gas-to-liquid salt heat transfer.

1.2 IHX Functions and Requirements

This section summarizes the functions and requirements that are used as the basis for the present IHX evaluation. In developing these functions and requirements, the starting point was the reference PBMR NGNP Preconceptual Design that is described in the Preconceptual Design Report (PCDR) (Ref. 0). The reference Preconceptual Design is based upon the Printed Circuit Heat Exchanger (PCHE), a plate-type microchannel heat exchanger, which is coupled to the PHTS on the shell-side of the heat exchanger.

As initially noted in the PCDR, and confirmed in Section 1.1 of this report, the plate-fin heat exchanger concept is a promising IHX design option, if questions related to its long-term reliability in service can be adequately addressed. On this basis, the plate-fin heat exchanger has been selected as the principal focus of the present HTS evaluation, though the PCHE is viewed as an equally promising IHX candidate. In conjunction with the plate-fin technology, two additional system-level alternatives are being evaluated within this present study. These relate to which side of the heat exchanger should be coupled to the PHTS and the direction of pressure biasing. It should be noted that the evaluation of these alternatives via their specification in the functions and requirements that follow does not imply their selection or a change from the PCRD reference design. These attributes will be finally confirmed in the Conceptual Design Phase that follows.

In the sections below, the Nuclear Heat Supply System (NHSS) steady state operation conditions to be applied in this study are first summarized. This is followed by a summary of more detailed functions and requirements for the IHX.

1.2.1 NHSS Steady State Operating Conditions

The NHSS schematics presented in Figure 1-2 and Figure 1-3 serve as basis for the IHX steady state performance evaluation for a ROT of 950°C and 800°C respectively. The HTS comprises the PHTS and SHTS as described in PCDR Section 6.2. An update of the reference steady state operating conditions is presented in Figure 1-2, with the only adjustment from the PCDR Section 3 reference being that the SHTS pressure has been increased from 8.5 MPa to 9.1 MPa, with a consequent decrease in SHTS blower size.

For the purposes of the present evaluation, the SHTS pressure was increased relative to the PCRD reference design in order to provide a slight secondary-to-primary pressure bias. Although primary-to-secondary bias allows rapid detection of small primary-to-secondary leaks via radionuclide monitoring, the secondary-to-primary bias ensures that IHX leaks will not lead to SHTS contamination. Since the plate-fin heat exchanger design is potentially sensitive to the direction of pressure differential, the initial assumption is that the PHTS is coupled to the core-side, rather than the shell-side, as in the PCDR design. This results in the IHX core cells being loaded in compression, rather than tension, during steady state or normal operations. Both the reference direction of pressure bias and the side of the IHX to be coupled to the PHTS were further evaluated in this study (see Section 3.4) and are to be confirmed during conceptual design.

Steady state operating conditions are based on the assumptions that there is a 3 MWt heat loss in the reactor, that the helium blowers will be designed to perform at 80% isentropic efficiency (with 5% electric to thermal loss), that the piping will be sized to ensure less than 0.2% fractional pressure loss in each pipe, that the IHX design ensures less than 1.23% fractional pressure loss per side for the overall IHX, and that the PCHX and SG are designed to ensure less than 200 kPa and 42 kPa pressure loss, respectively.

Figure 1-3 presents steady state operating conditions for a ROT of 800°C, assuming use of the same physical hardware. For a ROT of 800°C, the operating RIT and power level (475MWt) was selected such that the PHTS blower non-dimensional mass flow rate is essentially constant (compared to the reference) to ensure that the same blower for the 950°C ROT reference can be applied for the 800°C ROT case. Note that the PBMR RIT is limited to 350°C for a ROT of 950°C due to a reactor differential-temperature constraint. Alternatively, the power level can be maintained at 500MWt,implying that the PHTS blower will either need to be over-designed or replaced in service to operate at both 950°C and 800°C ROT.

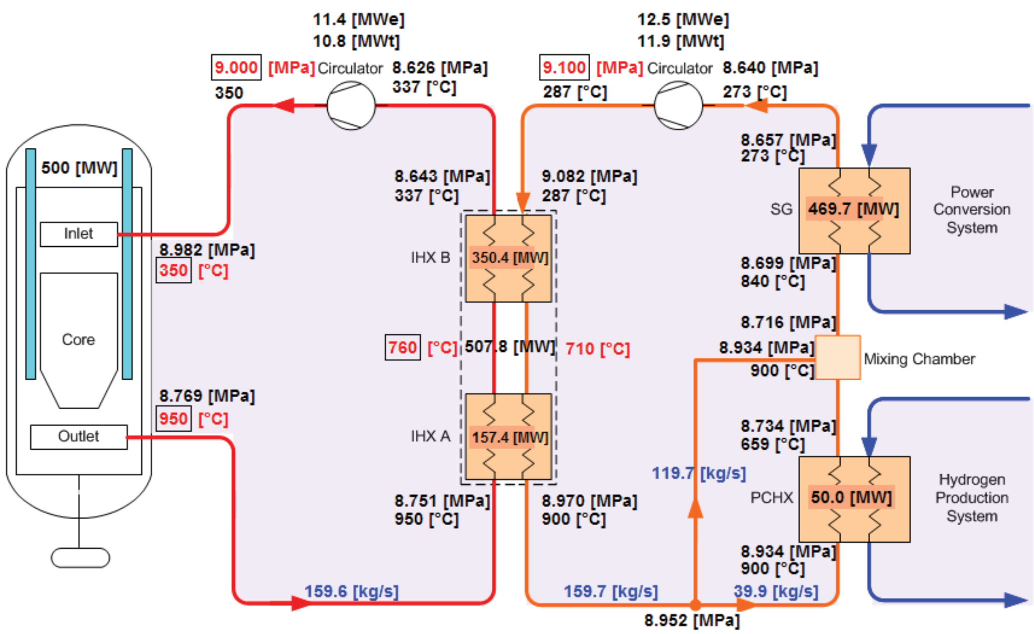


Figure 1-2 Steady State Operating Conditions for 950°C ROT (Updated Reference)

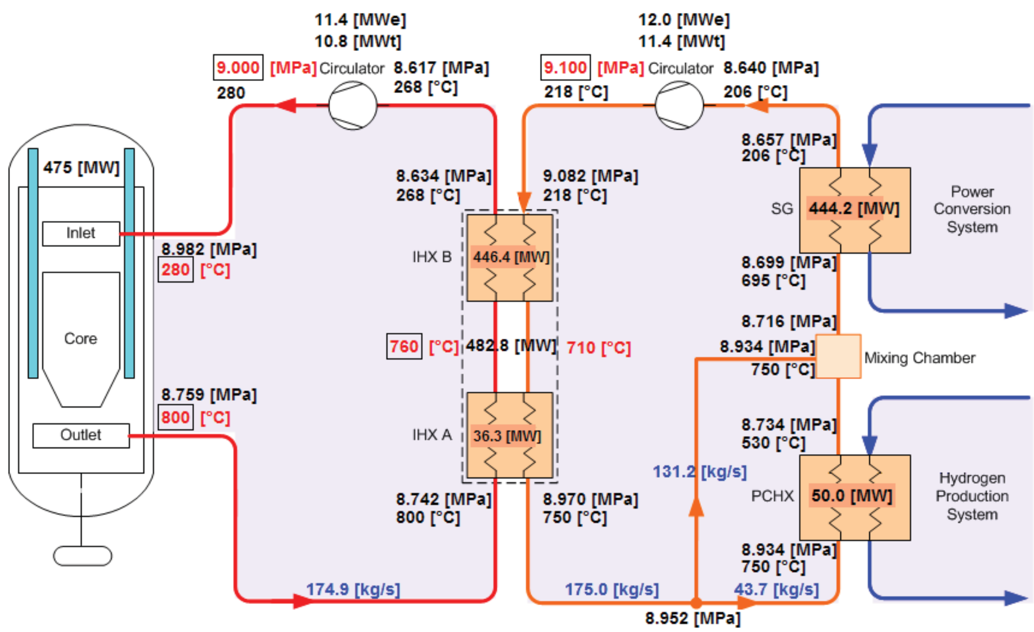


Figure 1-3 Steady State Operating Conditions for 800°C ROT

The IHX transfers thermal energy between the Primary Heat Transport System (PHTS) and the Secondary Heat Transport System (SHTS). The PHTS comprises the primary piping, primary circulator and primary helium working fluid. By definition, the IHX is considered part of the PHTS. Its main function is to transport thermal energy from the reactor to the SHTS (see PDCR Section 6.2.1.1.1 for further functions). The SHTS comprises the secondary piping, secondary circulator and secondary helium working fluid. Its main function is to transport thermal energy from the IHX to the Process Coupling Heat Exchanger and Steam Generator (see PDCR Section 6.2.2.1.1 for further functions).

The Intermediate Heat Exchanger (IHX) comprises:

- Heat transfer surface and/or modules containing the heat transfer surface.
- Headers and/or piping that provide a transition between the heat transfer surface and/or modules and the PHTS/SHTS piping.
- Internal structures that provide for support (steady state, transients and seismic loading) of the IHX and related internal components within the IHX vessel.
- Thermal baffles and/or insulation that is attached to the above IHX components.

The IHX Vessel comprises that part of the helium pressure boundary which encloses the above described components of the IHX. The IHX vessel includes internal support features, incorporated within the vessel structure, that interface with the IHX internal supports. It also includes thermal baffles and/or insulation that are directly attached to the vessel itself. The allocation of the IHX vessel (or parts thereof) as being part of the PHTS or SHTS will depend upon which fluids (PHTS or SHTS) are contained within the shell-side of the heat exchanger. This, in turn will be subject to the further selection of which circuit (PHTS or SHTS) will be coupled to the “shell” side of the heat exchanger).

1.2.2 Functions

The functions of the IHX are to:

- Transfer thermal energy between the PHTS and SHTS.
- Provide separation between the PHTS and SHTS helium working fluids.

1.2.3 Requirements

The requirements provided in Table 1-3 are specifically provided for the purposes of this Special Study. They may or may not be consistent with the requirements for the PCDR design or those ultimately selected for the NGNP as a whole.

The requirements identified as "Fixed" are assumed as the basis for this special study. Requirements identified as "Subject to Review" (STR) were tentative selections from the Pre-conceptual Design that are to be further explored as part of this special study and future studies. Items identified as “Preference” are not fixed requirements, but simply indicate a preference from NHSS viewpoint.

Table 1-3 IHX Requirements

Requirement	Fixed	Preference	Subject to Review	Notes / Rationale
1. Interface Requirements				
a) The IHX headers and piping shall be designed to interface with the PHTS and SHTS piping and the associated internal piping components.	X			Internal piping components refer to, amongst others, internal insulation and flow paths for cooling flows. See Figure 1-4 together with Figure 1-5 to Figure 1-10 for the piping interface dimensions.
b) Pipe 1 and Pipe 2 (see Figure 1-4) shall be co-axial pipes.	X			Co-axial piping is employed to enable the pressure boundary to be cooled with cooling flow from the blower outlet.
c) The PHTS IHX-B outlet piping should be at the top (or close to top) of vessel.		X		The PBMR inlet is at the top of the RPV, thus the simplest return piping is facilitated by an IHX-B outlet at the top.
d) The PHTS IHX-A inlet piping should be located towards the bottom of IHX.		X		Piping at bottom of PHTS IHX-A inlet will simplify piping layout from reactor.
e) The IHX internal structures and fluid flow shall ensure that the vessel temperature be limited to 371°C during normal operation.	X			The IHX vessel material shall be SA-508/SA-533 low-alloy steel (which is limited to <371°C during normal operation). For this reason, it is preferred that the coolest gas in the shell-side of the IHX be closest to the vessel and the hot gas be the furthest away.
f) The IHX-B vessel and internals shall be configured to support the mounting of the PHTS circulator directly on the vessel at the PHTS outlet side.			X	This requirement will be further evaluated when the circulator & integration studies position the circulator.
g) A self-acting helium check valve shall be integrated with the main circulator to limit backflow through the main loop. (Backup provisions shall be incorporated for manual actuation of the check valve.)			X	The integration of the valve with the circulator vs. separate location in the piping is subject to review. If the circulator and/or valve are integrated with the IHX vessel, this must be considered in the IHX/IHX vessel layout.

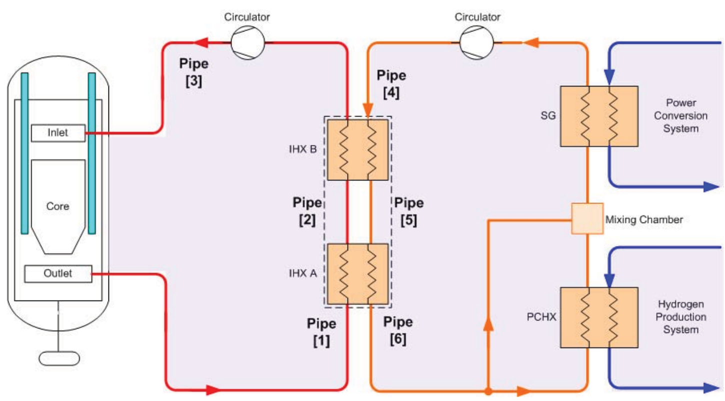


Figure 1-4 IHX/Piping Interface Drawing Pipe Definitions

Table 1-3 IHX Requirements (cont'd)

Requirement	Fixed	Preference	Subject to Review	Notes / Rationale
2. System Configuration and Essential Features				
a) The IHX design shall have a single hot inlet pipe from the Reactor (PHTS).	X			If there are multiple parallel IHXs, the branching must be in the PHTS/SHTS piping.
b) The IHX design shall have a single hot outlet pipe to the Process Coupling Heat Exchanger (SHTS).	X			If there are multiple parallel IHXs, the branching must be in the PHTS/SHTS piping.
c) The IHX design shall have a single cold outlet pipe to the Reactor (PHTS).	X			If there are multiple parallel IHXs, the branching must be in the PHTS/SHTS piping.
d) The IHX design shall have a single cold inlet pipe from the Process Coupling Heat Exchanger (SHTS).	X			If there are multiple parallel IHXs, the branching must be in the PHTS/SHTS piping.
e) The working fluids in both the PHTS and SHTS shall be helium.	X			
f) The IHX that couples the PHTS and SHTS shall be comprised of a full-lifetime low-temperature section designated as IHX-B and a replaceable high-temperature section (IHX-A).			X	Conditional requirement based on conceptual design as per PCDR. Subject to the ability / cost of provision of a complete IHX capable of operating for the full design lifetime of the plant.
g) The size ratio of IHX-B:IHX-A shall be as large as practicable.	X			
h) IHX-A and IHX-B shall be housed in separate IHX vessels.			X	Conditional requirement subject to the design decision of the ability of the IHX to survive the design life.
3. Operational Requirements				
a) The IHX, except for the replaceable high-temperature components of IHX-A, shall be designed for an operating life of 60 years.	X			The temperature breakpoint between IHX-A and IHX-B should be reviewed. The essential requirement is that IHX-B is a full-lifetime component.
b) The high-temperature components of IHX-A shall be designed for a minimum operating life of [10] years.	X			
c) The IHX shall be designed to transfer nominally 510 MW (including primary circulator power) from the PHTS to the SHTS at the design conditions listed below.	X			

Table 1-3 IHX Requirements (cont'd)

Requirement	Fixed	Preference	Subject to Review	Notes / Rationale
d) The pressure loss across primary side and also across secondary side of IHX shall be smaller than 1.23 % of its respective inlet pressures.	X			$\left(\frac{\text{IHX A}_{\text{inlet}} - \text{IHX B}_{\text{outlet}}}{\text{IHX A}_{\text{inlet}}}\right)_{\text{Primary}} < 1.23\%$ $\left(\frac{\text{IHX B}_{\text{inlet}} - \text{IHX A}_{\text{outlet}}}{\text{IHX B}_{\text{inlet}}}\right)_{\text{Secondary}} < 1.23\%$ The 1.23% value was derived from analogous pressure loss estimates from DPP.
e) IHX-A PHTS inlet pressure shall be 8750 kPa.	X			
f) The PHTS/SHTS shall be essentially pressure-balanced.	X			
g) IHX-B SHTS inlet pressure shall be 9080 kPa.			X	Pressure bias evaluated as part of this study and to be confirmed in conceptual design.
h) The PHTS/SHTS pressure drop rate shall be such that the SHTS pressure is always higher that the PHTS pressure.			X	
i) Primary-side IHX inlet/outlet shall be 950°C/337°C.	X			
j) Primary-side and Secondary-side IHX mass flow rate shall be 160 kg/s.	X			
k) The steady state secondary side IHX-A outlet temperature shall not be lower than 900°C.	X			
l) The IHX shall be able to accommodate 600 start-up/shut-down cycles. (Transient 1).	X			See Section 2.2.1 and 2.2.2 for definition of Transient 1.
m) The IHX shall withstand a 9 MPa pressure differential resulting from loss of SHTS pressure from full power operating conditions for at least one event without consequent failure of the PHTS/SHTS pressure boundary (Transient 2).	X			See Section 2.2.1 and 2.2.3 for definition of Transient 2.

Table 1-3 IHX Requirements (cont'd)

Requirement	Fixed	Preference	Subject to Review	Notes / Rationale
4. Structural Requirements				
a) The IHX vessel diameter shall be smaller than 6 m; hence, IHX internals shall be designed to fit within a 6 m vessel.		X		Construction constraint.
5. Environmental Requirements				
a) Those portions of the IHX exposed to PHTS coolant helium shall be designed to resist chemical impurities within the limits [TBD] specified for the primary coolant.			X	
b) Those portions of the IHX exposed to SHTS coolant helium shall be designed to resist chemical impurities within the limits [TBD] specified for the secondary coolant.			X	
c) The IHX shall be designed for an Operating Basis Earthquake that exerts an impact of [TBD] on the IHX and Design Basis Earthquake of [TBD].			X	OBE needs to be confirmed. Also, need to evaluate whether the PHTS/SHTS interface needs to remain intact for DBE. The actual OBE and DBE impacts on the IHX will be site and design (building and supports) specific.
6. Instrumentation and Control Requirements				
				None at this stage.
7. Availability and Reliability				
a) The inherent availability (safe life design) of the IHX shall be $\geq$ 99.98%			X	
8. Maintenance Requirements				
a) The IHX shall not require preventative maintenance.	X			
b) The IHX shall include provisions for detecting and locating leaks and for repairing, isolating and/or replacing failed components		X		The leak detection capability may be implemented elsewhere in the HTS, however locating and repairing or isolating leaks remains an IHX requirement. This requirement is subject to the future development of an overall HTS maintenance philosophy that includes consideration of the tradeoffs between maintainability and availability.

Table 1-3 IHX Requirements (cont'd)

Requirement	Fixed	Preference	Subject to Review	Notes / Rationale
8. Maintenance Requirements (cont'd)				
c) The PHTS side of the IHX shall be designed to operate for its full design life in the presence of circulating dust.	X			Dust profile to be evaluated in a companion Contamination Control Study.
9. Transport Requirements				
a) Design features shall be included to allow for transportation of sub-assemblies with final assembly on site.	X			The current transport constraint for the INL site is 3.5 m by 24 m. Since the RPV will be fabricated/welded on site, the equipment will be on site to assemble the IHX - hence current assumption is that it is not required to impose specific transportability requirements on IHX. It is noted that transportability constraints are site specific.
10. Testing, Qualification, Commissioning (TQC)				
a) Provisions shall be made for pressure testing of the PHTS in accordance with ASME pressure vessel requirements with the SHTS at ambient pressure.	X			The entire PHTS must be pressure tested on site after assembly in the field. The IHX internals would be in place at this time.

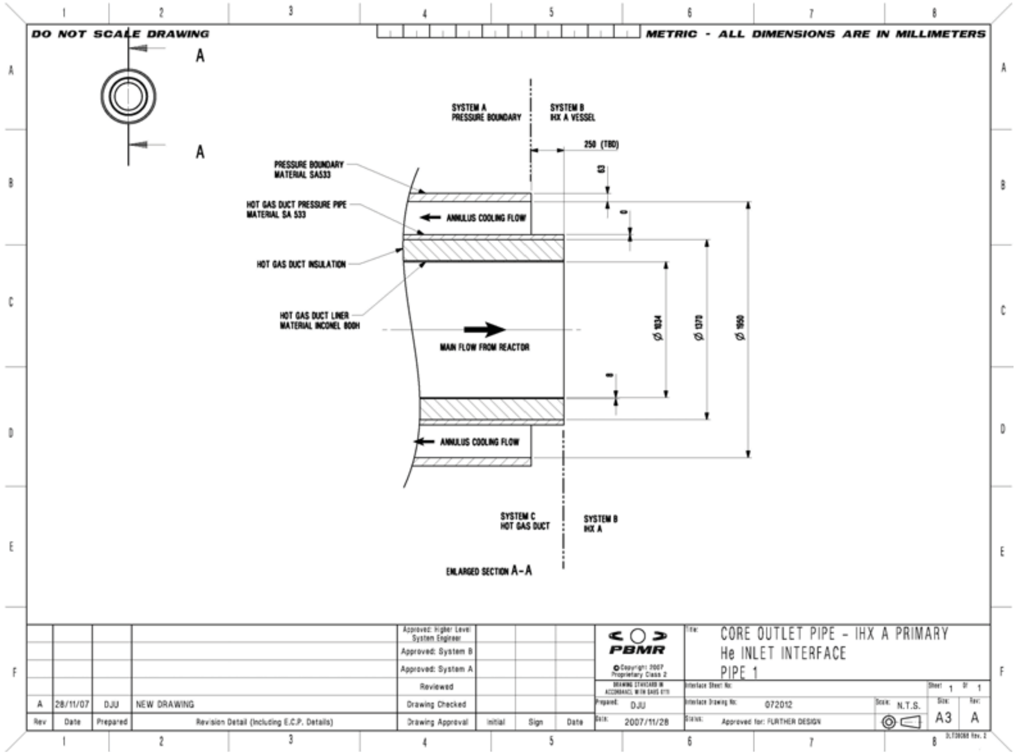


Figure 1-5 IHX/Piping Interface Drawing Pipe 1

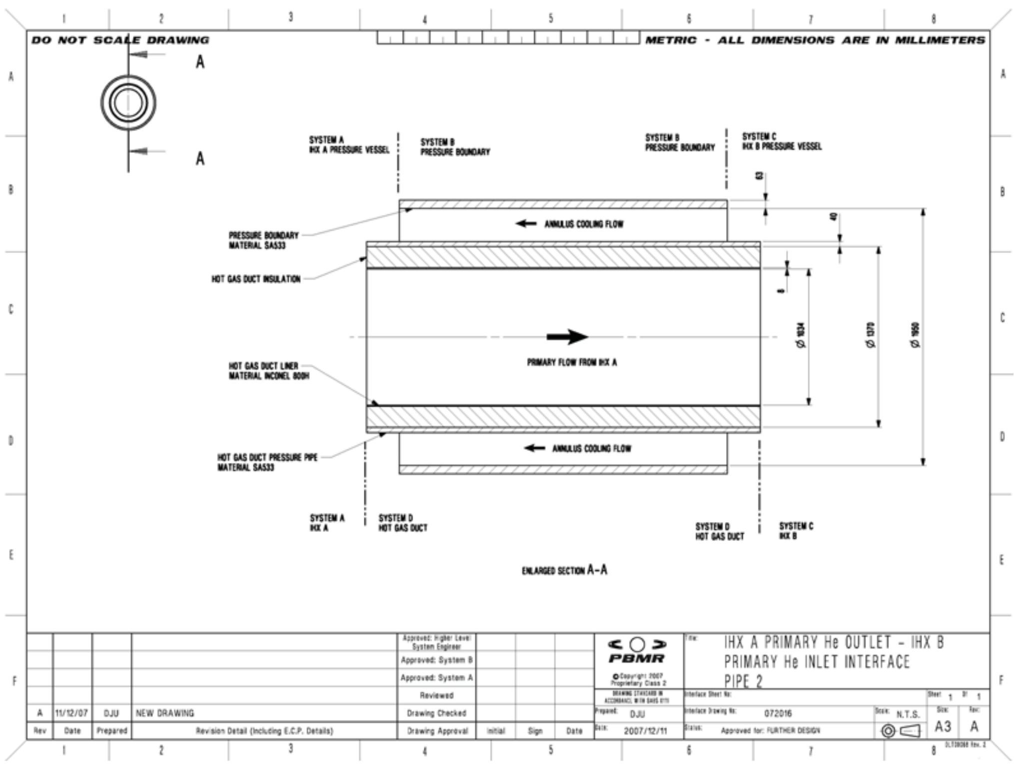


Figure 1-6 IHX/Piping Interface Drawing Pipe 2

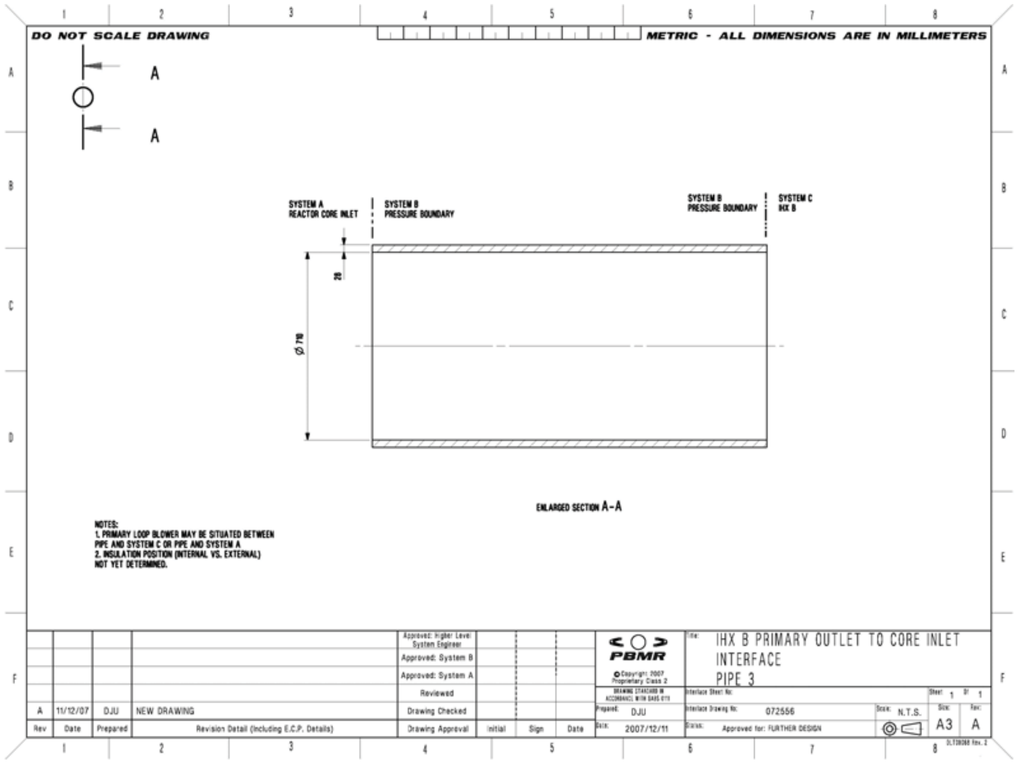


Figure 1-7 IHX/Piping Interface Drawing Pipe 3

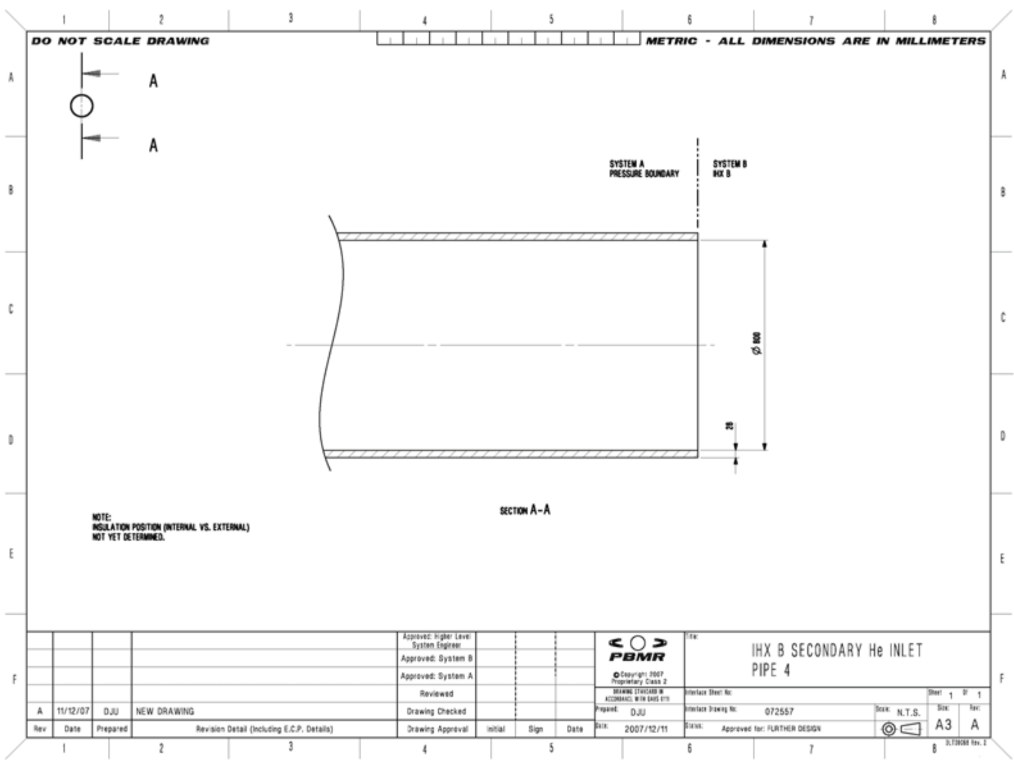


Figure 1-8 IHX/Piping Interface Drawing Pipe 4

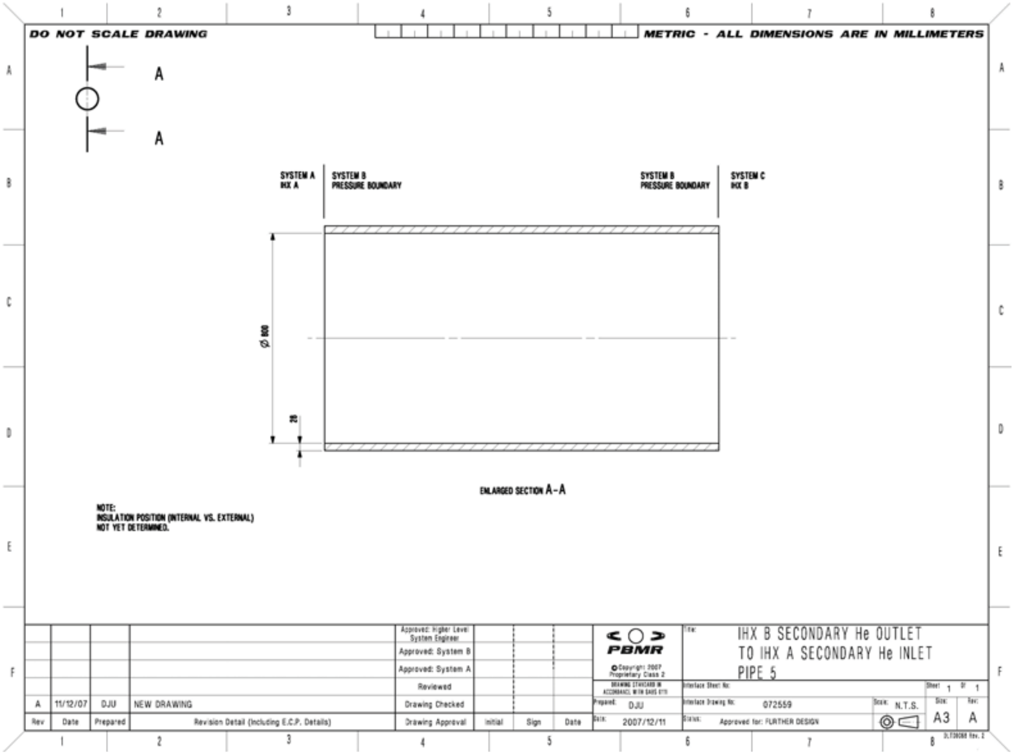


Figure 1-9 IHX/Piping Interface Drawing Pipe 5

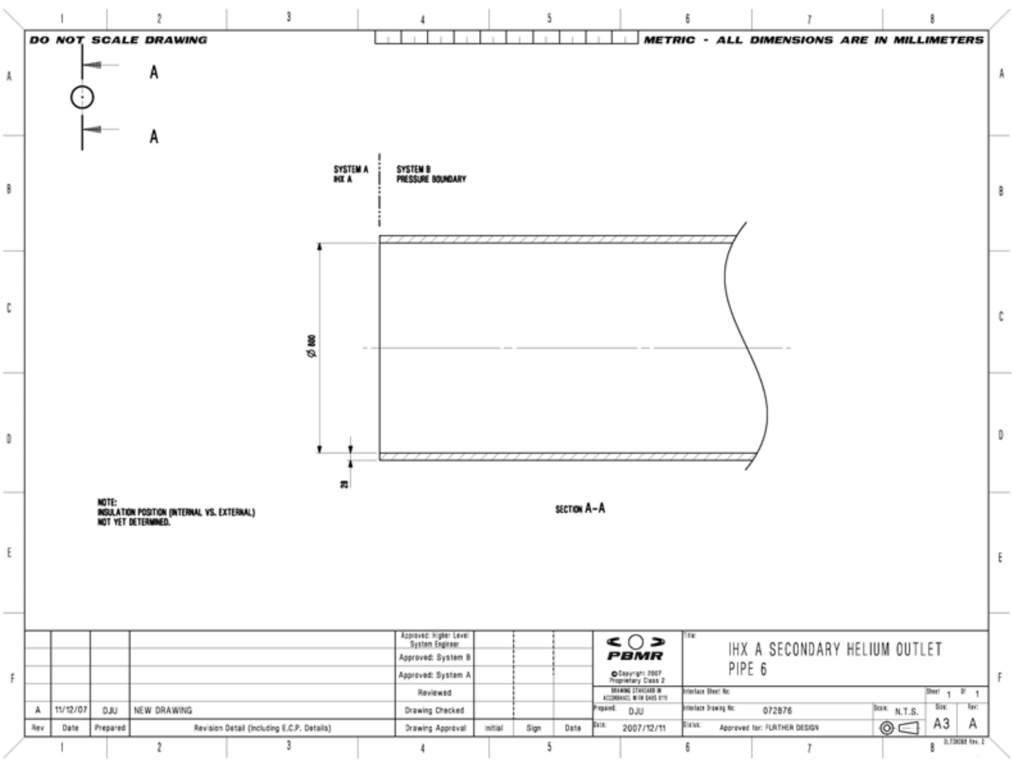


Figure 1-10 IHX/Piping Interface Drawing Pipe 6

1.3 System-Level Integration Options

The objective of this section is to motivate the selection of two representative NHSS system-layouts, one for coupling the PHTS to the "core-side" of the IHX and one for coupling the PHTS to the "shell-side" of the IHX. In this context, the "core-side" of the IHX is analogous to the "tube-side" of conventional shell-and-tube heat exchangers (See Figure 1-11). The qualitative comparison of the various system-level layout options includes consideration of piping, maintenance and blower location. The main focus is on the relative placement of the IHX's and the associated implications. The two proposed representative system layouts will be further evaluated in Section 3.4.

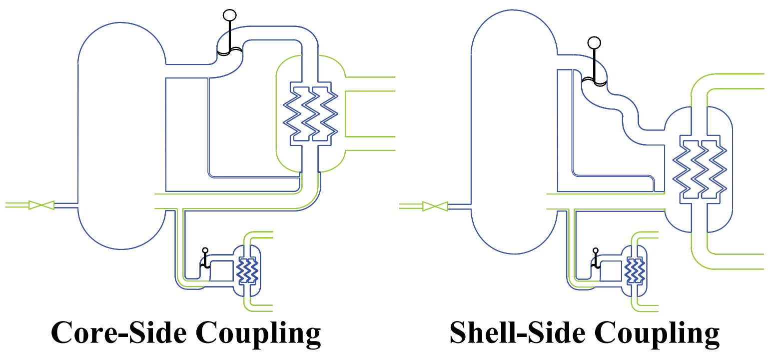


Figure 1-11 Core- and Shell-Side IHX Coupling

Two concepts for coupling the primary flow to the IHX core-side and three concepts for coupling the primary flow to the IHX shell-side were considered (Figure 1-12).

- Layout P1 and P2 based on <u>primary</u> flow inlet and outlet on the core-side of the IHX
- Layout S1, S2 and S3 based on <u>secondary</u> flow inlet and outlet on the core-side of the IHX

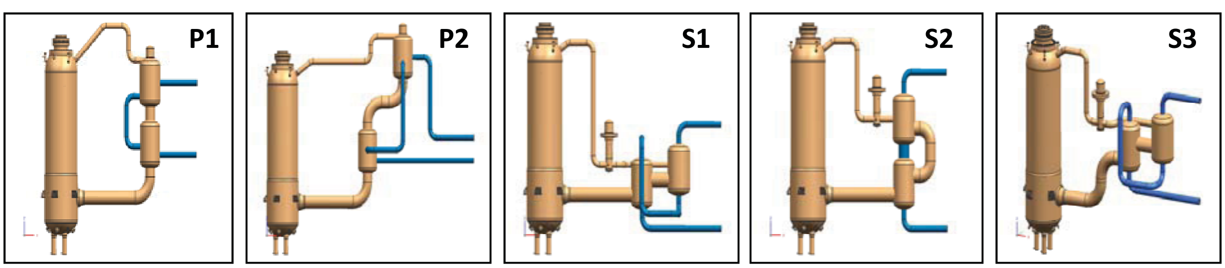


Figure 1-12 Layout Options

The following trade-offs are considered for the layout evaluation:

- **PHTS Piping**, including the length of actively-cooled high-temperature piping containing Hot Gas Ducts (HGDs), the length of conventional pipes, complexity of pipes containing HGDs, provisions for thermal expansion of pipes and provisions for the support of IHX vessels and pipes.
- **Maintenance** including removal/replacement of IHX-A, which is expected to have limited life relative to the plant as a whole, access for leak detection and plugging, maintenance dose rate at IHX-A due to the neutron activation of the metallic components.
- **Circulator Position**

1.3.1 Layout Assumptions

The influence of IHX core dynamics (preference for shell- vs. core-side coupling to the PHTS from the IHX core viewpoint during transients) and pressure bias (PHTS vs. SHTS at higher pressure during normal operation) are considered in Section 3.4. For this initial layout screening, the following assumptions apply:

- Only the reactor outlet pipe and PHTS interconnect (IHX-A-to-IHX-B) piping has concentric cooling.
- All SHTS piping comprises single, internally insulated pipes (not actively cooled).
- The IHX internals are designed for core-side access for examination/plugging.

1.3.2 Layout Evaluation

The reference PCDR layout and the five additional layout options developed within this study were compared qualitatively by assigning a rating of “Good”, “OK”, “Challenge” or “Not Acceptable”. An evaluation table is presented for each option in the subsections that follow. A summary of the assessment is provided in Section 1.3.3, along with the conclusions of the layout evaluation.

1.3.2.1 PCDR Reference

For comparison purposes, the NHSS layout as described in the PCDR is presented in Figure 1-13.

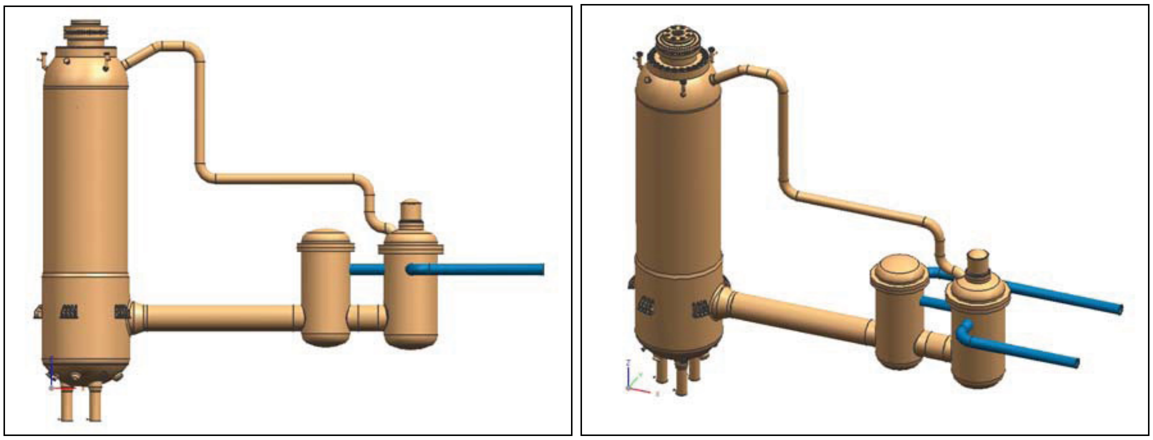
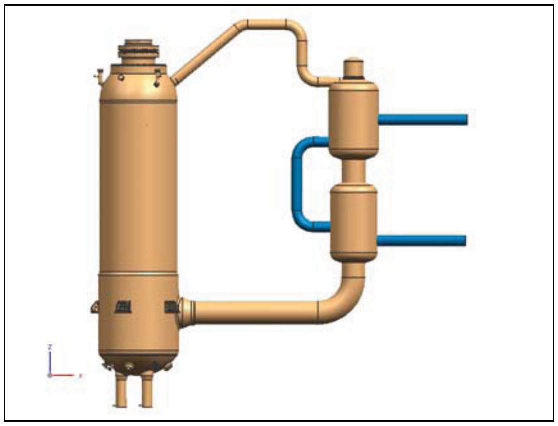


Figure 1-13 NGNP PCDR Layout

Table 1-4 NGNP PCDR Layout

Consideration	Description	Conclusion
General Notes		
The PCDR reference layout incorporates a printed circuit heat exchanger.		
The shell-side of the IHX is coupled to the PHTS and the core-side to the SHTS.		
PHTS Piping		
Length of pipes containing HGDs	The reactor outlet pipe and the pipe connecting IHX-A to IHX-B are as short as possible.	Good
Length of conventional pipes	The reactor inlet pipe is long with a few bends to accommodate thermal expansion.	OK
Complexity of pipes containing HGDs	Reactor outlet pipe and pipe connecting IHX-A to IHX-B are straight sections.	Good
Thermal expansion/supports	The RPV will be supported fixed. The IHX vessels will have supports that resist lateral and vertical movement, but allow movement along the axis of the reactor outlet pipe.	OK
Maintenance		
Removal of IHX-A	The vessel of IHX-A can be removed vertically. The removal of IHX-A is independent of IHX-B. The reactor inlet pipe needs to be removed, as it is routed above IHX-A.	Good
Access for leak detection and plugging	Access to the IHX cores is very difficult, as there is no linear access (see internal piping shown in Ref. 1-1).	Not Acceptable
Maintenance dose rate	Neutron activation of the IHX vessel and internals is expected, due to streaming from the core outlet plenum through the straight reactor outlet pipe/HGD to IHX-A.	Not Acceptable
Circulator Position		
Circulator position	The circulator is well supported and integrated with the vessel of IHX-B	Good

1.3.2.2 Layout P1



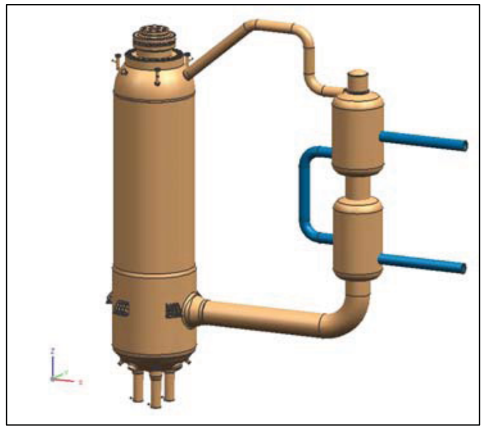


Figure 1-14 Layout Option P1

Table 1-5 Layout Option P1

Consideration	Description	Conclusion
General Notes		
The IHX is of the plate-fin type.		
The shell-side of the IHX is coupled to the SHTS and the core-side to the PHTS.		
PHTS Piping		
Length of pipes containing HGDs	The reactor outlet pipe is longer to include a single bend. The pipe connecting IHX-A to IHX-B is as short as possible.	OK
Length of conventional pipes	The reactor inlet pipe is short with a few bends to accommodate thermal expansion.	Good
Complexity of pipes containing HGDs	Reactor outlet pipe includes a single bend. Pipe connecting IHX-A to IHX-B is a straight section. (Note: bends in the HGD are standard practice and not much more complex than straight sections.)	Good
Thermal expansion/supports	The RPV will be supported fixed. The IHX-A vessel will be supported on trunnions that resist lateral and vertical movement, but allow rotational movement for thermal expansion of the reactor outlet pipe.	OK
Maintenance		
Removal of IHX-A	The vessel of IHX-A can be removed vertically but requires removal of IHX-B or provisions to move IHX-A laterally before the vertical lift.	OK/Challenge
Access for leak detection and plugging	Access to the IHX cores is challenging. Access is via the reactor outlet pipe/ HGD and the PHTS pipe/HGD between IHX-A and IHX-B. Requires opening the PHTS.	Challenge
Maintenance dose rate	Very little activation of the IHX vessel and internals expected, as the bend avoids direct neutron streaming from the core outlet plenum. A shielding floor can also be installed between the reactor outlet pipe and the IHX. Leak detection and plugging requires access for from PHTS side.	OK
Circulator Position		
Circulator position	The circulator is well supported and integrated with the vessel of IHX-B. The blower can also be integrated into the reactor inlet pipe, as per layout options S1 and S2, if preferred.	Good

1.3.2.3 Layout P2

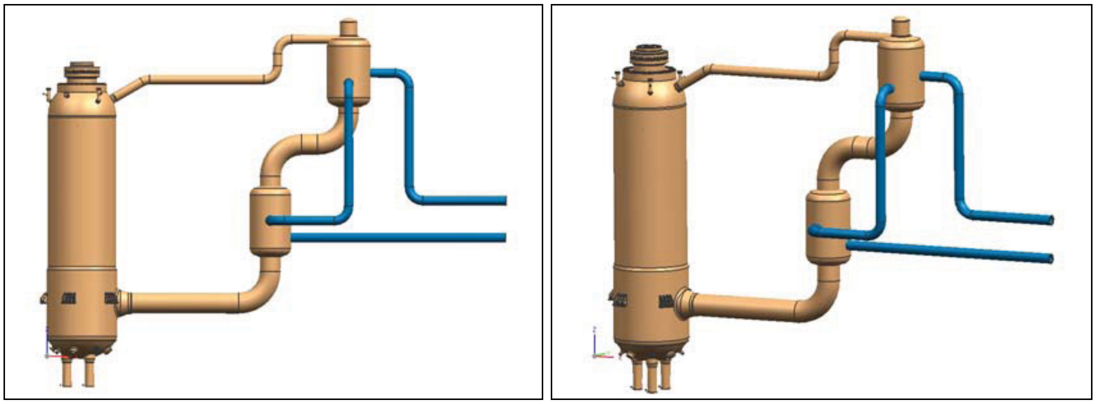
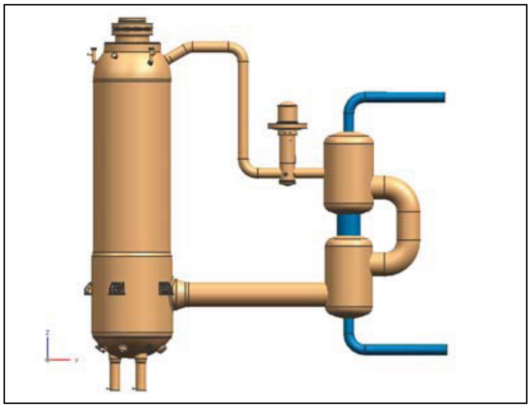


Figure 1-15 Layout Option P2

Table 1-6 Layout Option P2

Consideration	Description	Conclusion
General Notes		
The IHX is of the plate-fin type.		
The shell-side of the IHX is coupled to the SHTS and the core-side to the PHTS.		
PHTS Piping		
Length of pipes containing HGDs	The reactor outlet pipe is longer to include a single bend. The pipe connecting IHX-A to IHX-B is longer to include two bends.	OK
Length of conventional pipes	The reactor inlet pipe is short with a few bends to accommodate thermal expansion.	Good
Complexity of pipes containing HGDs	Reactor outlet pipe includes a single bend. Pipe connecting IHX-A to IHX-B has two bends and is more complex than the layout of Option P1.	OK
Thermal expansion/supports	The RPV will be supported fixed. The IHX vessels will be supported on trunnions that resist lateral and vertical movement, but allow rotational movement to accommodate thermal expansion of the reactor outlet pipe.	Challenge
Maintenance		
Removal of IHX-A	The vessel of IHX-A can be removed vertically. The removal of IHX-A is independent of IHX-B. The reactor inlet pipe need to be removed, as it is routed above IHX-A.	OK
Access for leak detection and plugging	Access to the IHX cores is challenging. Access is via the reactor outlet pipe/ HGD and the PHTS pipe/HGD between IHX-A and IHX-B. Requires opening the PHTS.	Challenge
Maintenance dose rate	Very little activation of the IHX vessel and internals expected, as the bend avoids direct neutron streaming from the core outlet plenum. A shielding floor can also be installed between the reactor outlet pipe and the IHX. Leak detection and plugging requires access for from PHTS side.	OK
Circulator Position		
Circulator position	The circulator is well supported and integrated with the vessel of IHX-B. The circulator can also be integrated into the reactor inlet pipe, as per layout options S1 and S2, if required.	Good

1.3.2.4 Layout S1



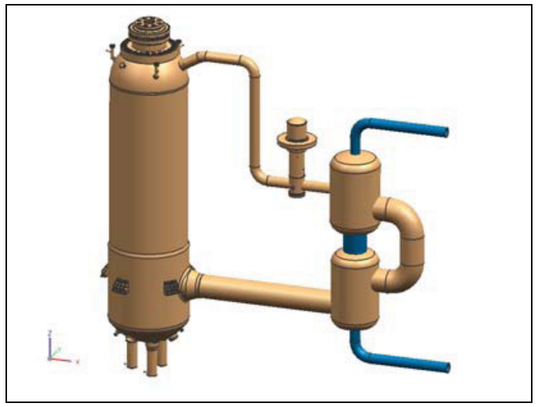
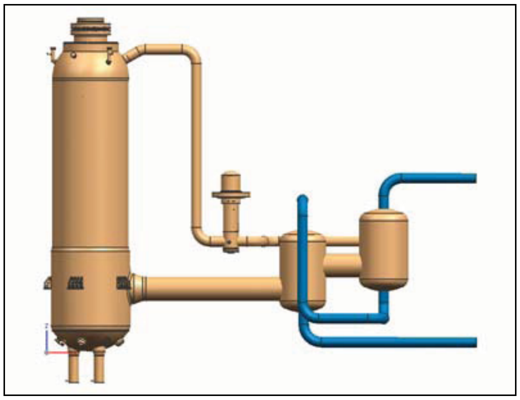


Figure 1-16 Layout S1

Table 1-7 Layout S1

Consideration	Description	Conclusion
General Notes		
The IHX is of the plate-fin type.		
The shell-side of the IHX is coupled to the PHTS and the core-side to the SHTS.		
PHTS Piping		
Length of pipes containing HGDs	The reactor outlet pipe is as short as possible. The pipe connecting IHX-A to IHX-B is longer to include two bends.	OK
Length of conventional pipes	The reactor inlet pipe is short with a few bends to accommodate thermal expansion.	Good
Complexity of pipes containing HGDs	Reactor outlet pipe is a straight section. Pipe connecting IHX-A to IHX-B has two bends.	OK
Thermal expansion/supports	The RPV will be supported fixed. The IHX-A vessel support will resist lateral and vertical movement, but allow movement along the axis of the reactor outlet pipe. The large diameter PHTS connection pipe between IHX-A and IHX-B may be a challenge.	Challenge
Maintenance		
Removal of IHX-A	The vessel of IHX-A can be removed vertically, but requires removal of IHX-B or provisions to move IHX-A laterally before the vertical lift.	OK/Challenge
Access for leak detection and plugging	Access to the IHX cores is via the single-wall SHTS piping. Need to open SHTS piping between IHX-A and IHX-B. No requirement to open the PHTS.	OK/Challenge
Maintenance dose rate	Neutron activation of the IHX vessel and internals is expected, due to streaming from the core outlet plenum through the straight reactor outlet pipe/HGD to IHX-A.	Not Acceptable
Circulator Position		
Circulator position	The circulator is integrated into the reactor inlet pipe and supported separately from the vessels.	OK

1.3.2.5 Layout S2



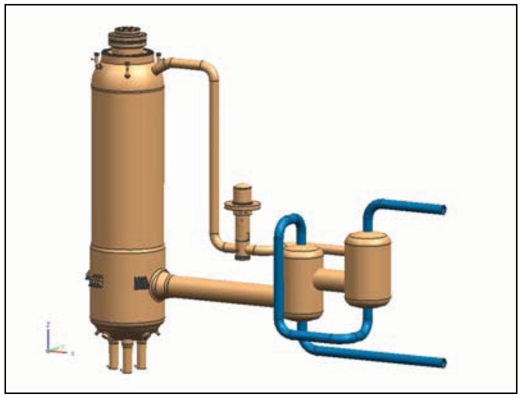
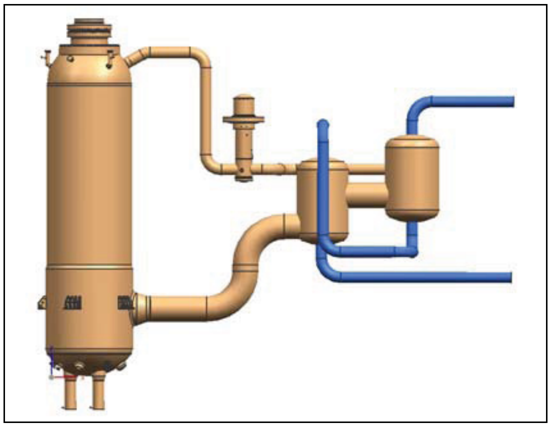


Figure 1-17 Layout S2

Table 1-8 Layout S2

Consideration	Description	Conclusion
General Notes		
The IHX is of the plate-fin type.		
The shell-side of the IHX is coupled to the PHTS and the core-side to the SHTS.		
PHTS Piping		
Length of pipes containing HGDs	The reactor outlet pipe and the pipe connecting IHX-A to IHX-B are as short as possible.	Good
Length of conventional pipes	The reactor inlet pipe is long with a few bends to accommodate thermal expansion.	OK
Complexity of pipes containing HGDs	Reactor outlet pipe and pipe connecting IHX-A to IHX-B are straight sections.	Good
Thermal expansion/supports	The RPV will be supported fixed. The IHX vessel supports will resist lateral and vertical movement, but will allow movement along the axis of the reactor outlet pipe.	OK
Maintenance		
Removal of IHX-A	The vessel of IHX-A can be removed vertically. The removal of IHX-A is independent of IHX-B.	Good
Access for leak detection and plugging	Access to the IHX cores is via the single-wall SHTS piping. No requirement to open the PHTS.	Good
Maintenance dose rate	Neutron activation of the IHX vessel and internals is expected, due to streaming from the core outlet plenum through the straight reactor outlet pipe/HGD to IHX-A.	Not Acceptable
Circulator Position		
Circulator position	The circulator is integrated into the reactor inlet pipe and supported separately from the vessels.	OK

1.3.2.6 Layout S3



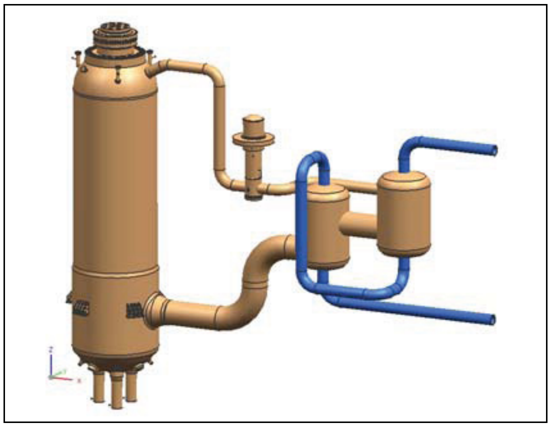


Figure 1-18 Layout S3

Table 1-9 Layout S3

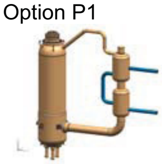
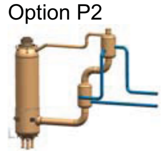
Consideration	Description	Conclusion
General Notes		
The IHX is of the plate-fin type.		
The shell-side of the IHX is coupled to the PHTS and the core-side to the SHTS.		
PHTS Piping		
Length of pipes containing HGDs	The reactor outlet pipe is longer to include two bends. The pipe connecting IHX-A to IHX-B is as short as possible.	OK
Length of conventional pipes	The reactor inlet pipe is long with a few bends to accommodate thermal expansion.	OK
Complexity of pipes containing HGDs	Reactor outlet pipe includes two bends. Pipe connecting IHX-A to IHX-B is a straight section.	OK
Thermal expansion/supports	The RPV will be supported fixed. The IHX-A vessel will be supported fixed.	OK/Challenge
Maintenance		
Removal of IHX-A	The vessel of IHX-A can be removed vertically. The removal of IHX-A is independent of IHX-B.	Good
Access for leak detection and plugging	Access to the IHX cores is via the single-wall SHTS piping. No requirement to open the PHTS.	Good
Maintenance dose rate	Very little neutron activation of metallic components of the IHX vessel and internals as there is no direct streaming and only limited neutrons will be reflected by the bend. A shielding floor can also be installed between the reactor outlet pipe and the IHX.	OK
Circulator Position		
Circulator position	The circulator is integrated into the reactor inlet pipe and supported separately from the vessels.	OK

1.3.3 Summary and Conclusions

The results of the layout evaluation are summarized in Table 1-10. Option P1 is preferred over option P2, due to smaller footprint and shorter HGD; however, recognizing that P2 offers better access for removal of IHX-A. Option S2 is preferred over Option S1, due to easier removal of IHX-A and IHX maintenance access. However, the maintenance dose rates for both Options S1 and S2 are viewed as being unacceptable.

S3 is a slight variation of S2 to overcome maintenance dose challenge, and is, hence, the preferred configuration for coupling the PHTS to the shell-side. Both Options P1 and S3 are viewed as designs that will meet the current IHX requirements, as defined earlier. The relative advantages and disadvantages of Options P1 and S3 with respect to IHX will be further evaluated in Section 3.4. However, it is noted that all system-level requirements will need to be considered before a final system-layout can be confirmed.

Table 1-10 Summary of Evaluation

Consideration	PCDR Reference 	Option P1 	Option P2 	Option S1 	Option S2 	Option S3 
Length of pipes containing HGDs	Good	OK	OK	OK	Good	OK
Length of conventional pipes	OK	Good	Good	Good	OK	OK
Complexity of pipes containing HGDs	Good	Good	OK	OK	Good	OK
Thermal expansion/ Supports	OK	OK	Challenge	Challenge	OK	OK/ Challenge
Removal of IHX-A	Good	OK/Challenge	OK	OK/ Challenge	Good	Good
Access for leak detection and plugging	Not Acceptable	Challenge	Challenge	OK/ Challenge	Good	Good
Maintenance dose rate	Not Acceptable	OK	OK	Not Acceptable	Not Acceptable	OK
Circulator position	Good	Good	Good	OK	OK	OK

1.4 Unit-Cell Intermediate Heat Exchanger

A compact-surface plate-fin heat exchanger concept has been conceived by Brayton Energy LLC with attributes well suited to the demands of the IHX. This heat exchanger technology and several integration schemes are discussed in the following paragraphs.

1.4.1 Core Concept

1.4.1.1 Construction

The unit-cell heat exchanger presented here falls into the broad category of "counterflow-plate-fin heat exchangers with crossflow headers". It differs from the typical construction in that the brazed unit is the minimum repeatable pressure-bounding fraction of the heat exchanger core, whereas an entire core is brazed with most plate-fin heat exchangers. Units are welded manifold-to-manifold to create cores, a construction economically produced by applying automated assembly methods. Also, thermo-mechanical stress in the cell and core is minimized by the narrow aspect ratio of the cores. The proposed geometry better manages thermal strains while avoiding the fluid's pressure-loss in the short, two-sided, crossflow headers.

A unit-cell is composed of two parting sheets and three layers of extended heat-transfer surface. Figure 1-19 illustrates these features and the manifold rings, incorporated as joining features and to resist hydraulic loads. While folded-wavy fin has been assumed here, other media such as metal-foam may be considered to further enhance performance.

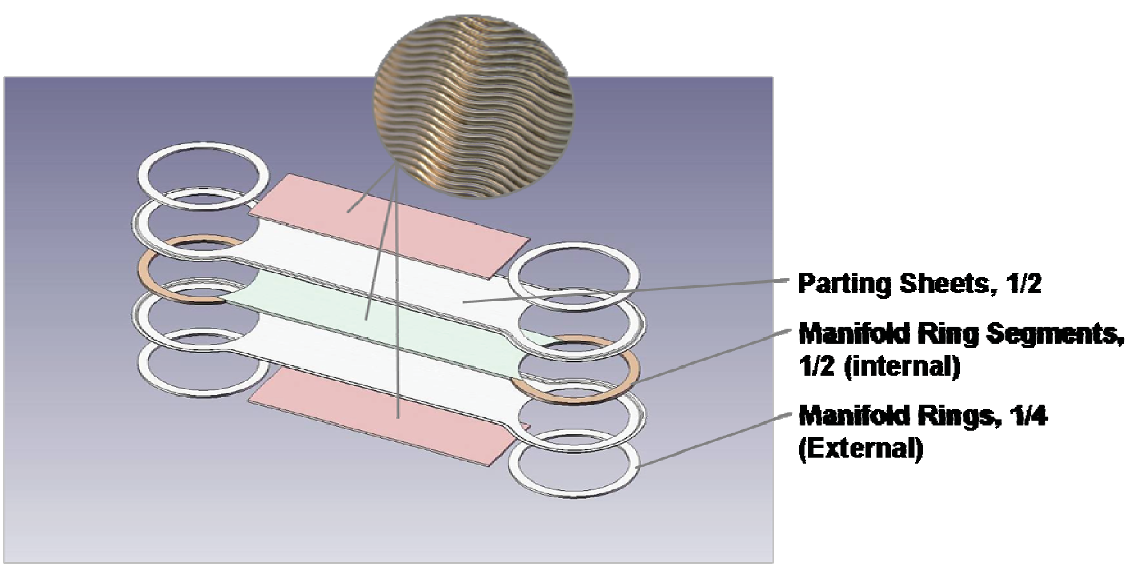


Figure 1-19 Exploded View of Unit-Cell Details

Parting sheets create the pressure boundary at the perimeter of the cell. One of two parting sheets used per unit-cell brazement is shown in Figure 1-20. As seen in Figure 1-20, the braze land is pressed into the sheets and is precisely dimensioned to one-half the internal fin-height. This ensures intimate contact between the sheets, fin, and periphery in each cell assembly.

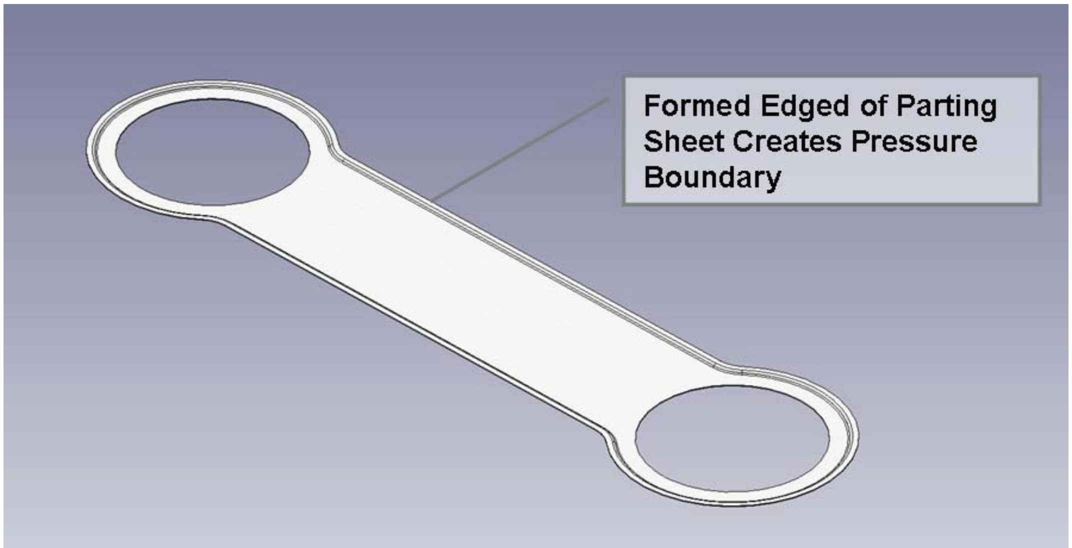


Figure 1-20 Parting Sheet Detail

The cell elements are assembled and furnace-brazed to complete a unit-cell as seen in Figure 1-21. Note that the manifold rings provide features for cell-to-cell welding. The heat exchange matrix comprises three layers of extended surface. This is an inspectable assembly that can be leak-tested and subjected to a high internal pressure to verify its integrity. Statistical sampling of cells for destructive testing is incorporated into the manufacturing process to economically obtain process-control data.

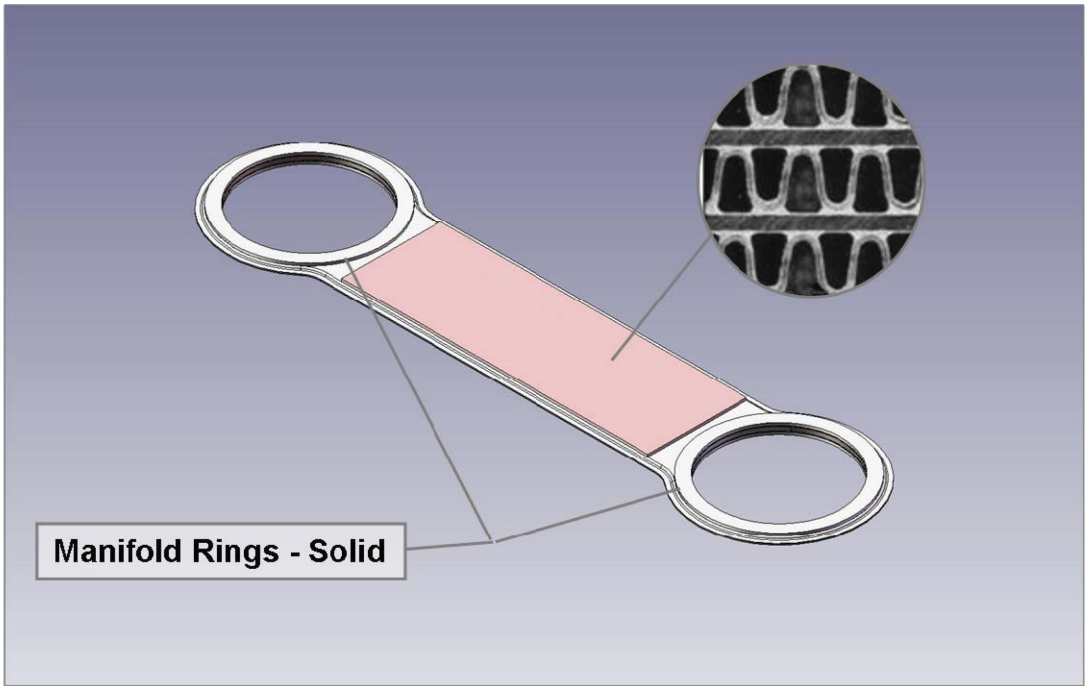


Figure 1-21 Unit Cell Brazement

As seen in Figure 1-22, cells are joined only at the manifolds by an orbital welding process, leaving the crowns of fins in the fin-fin plane between cells free to slip as required in response to thermal deflections of cores with changes in operating state. Sample locations of welds are shown in Figure 1-22.

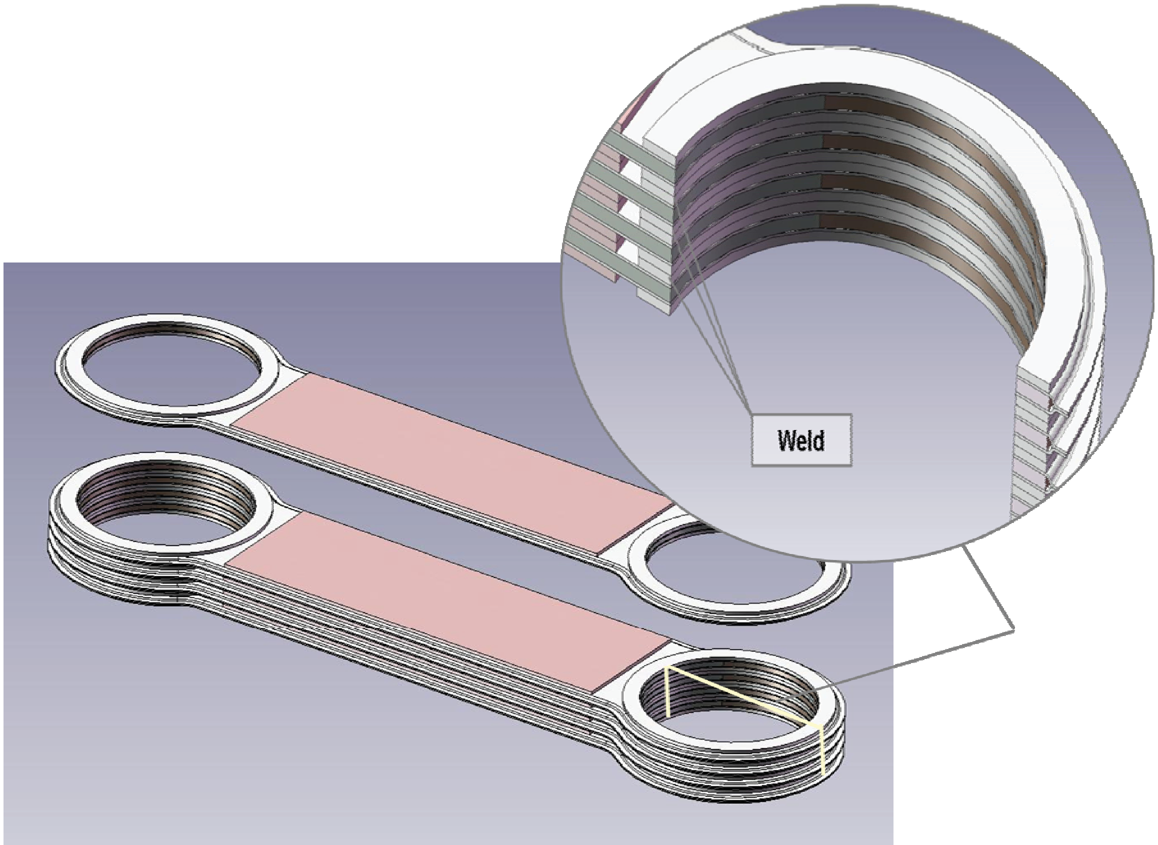


Figure 1-22 Core Under Construction

The core is leak-tested periodically during construction to assure hermeticity. As a complete assembly, with terminal flanges welded in place, final leak and pressure tests are conducted. There is little risk of failure at this point given the repeated intermediate checks during fabrication.

1.4.1.2 Function

Assignments of gas flows within the cell are done with these considerations:

- Stress state during normal operation
- Stress state in a loss-of-secondary-pressure event
- Maintainability considering radionuclide contamination of the primary side

The heat exchanger can function adequately with either the primary or secondary circuit coupled to the internal side of the cores. However, the preference from the heat exchanger viewpoint is that the higher pressure be assigned to the external side of the cores. With the external side at a slightly higher pressure, cells will be in compression during normal operation. This assures that pressure-induced stress has no tendency to open the pressure boundaries. With the reference HTS parameters selected for this study (Section 1.2.1), the SHTS pressure is set slightly higher than the PHTS pressure. Accordingly, the description within this section is based on the SHTS being coupled to the shell-side of the IHX. With this configuration, the direction of pressure would be reversed in a loss-of-secondary-pressure event and the stress would, indeed, be in the direction that tends to open the pressure boundary. However, the ability to survive this event would have been verified in development with characterization of cells at operating-temperature, and by pressure testing all cells and cores for structural flaws within the manufacturing process.

If the nominal pressure differential were to be reversed (PHTS pressure higher than SHTS pressure), assigning the secondary to the internal pass would guarantee that the cell pressure boundary would be compressed under all conditions (normal and loss-of secondary-pressure). This would alleviate any concern for rupture of a cell, as the tendency would be to collapse the cell. Concerns for migration of radiation from primary to secondary loops would need to be addressed, however, before adoption of this reversal in the nominal pressure-differential could be adopted.

Flow through an IHX-A cell is depicted in Figure 1-23. Primary gas flows between manifolds through the internal heat exchange passages. Secondary flow enters from both sides of the manifold at one end and flows counter to the primary through the outer passages of the cell and exits, left and right, around the primary inlet manifold.

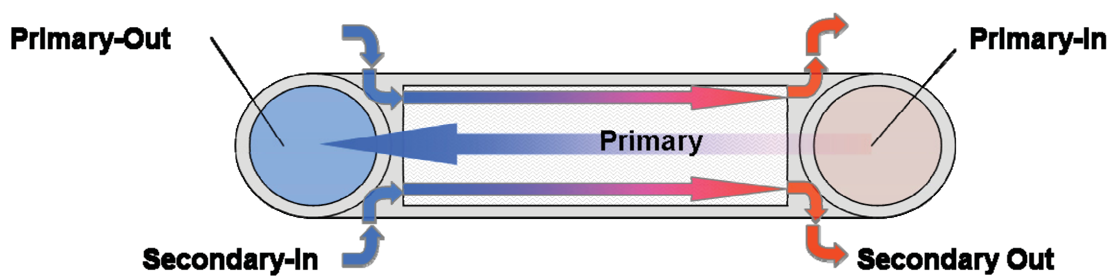


Figure 1-23 Flow Pattern through a Unit-Cell

Figure 1-24 shows a sample of a unit-cell in cross section. Primary flow is between parting sheets while secondary flow is above and below in the external fin passages.

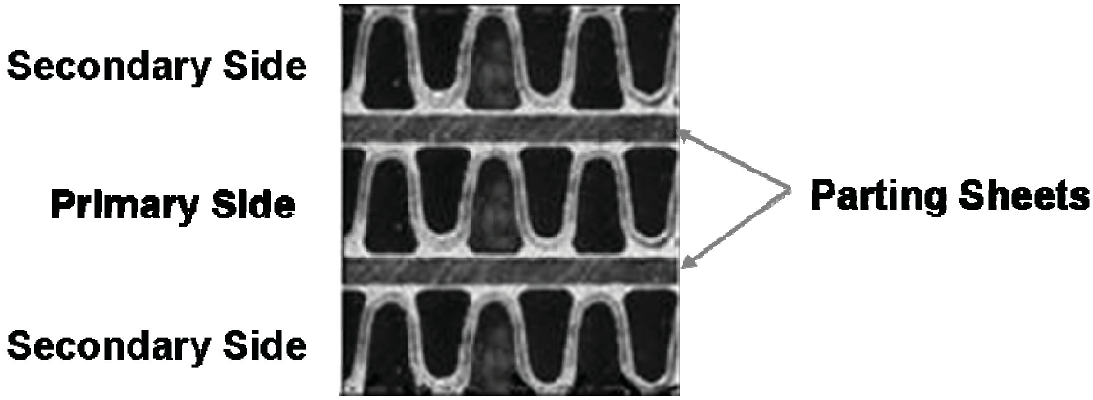


Figure 1-24 Sample Cross Section from a Unit-Cell

IHX-B cells are identical in construction to IHX-A, but with a longer, 300-mm counterflow length dimension to accomplish their greater assigned portion of the net required heat exchange.

1.4.1.3 Risks Related to Unit-Cell Cores

Table 1-11 presents a preliminary list of perceived risks associated with the cores only. These risks need to be scored in terms of their probabilities-of-occurrence and consequences should they occur. Suggestions for mitigation are included as well.

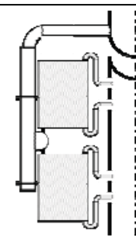
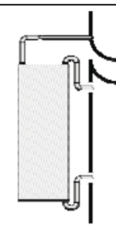
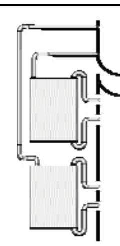
1.4.2 Unit-Cell Heat Exchanger Integration

A variety of integration concepts were conceived, arranging heat exchanger cores into vessels and plumbing them to the PHTS and SHTS streams in accordance with Functions and Requirements, Section 1.2.1. The unit-cell integration concepts are labeled A-C, and are summarized in Table 1-12.

Table 1-11 Unit-Cell Cores – Risks and Possible Mitigation

Perceived Risk	Possible Mitigation
Published heat transfer and friction data for "similar" surface leads to over or under-prediction of heat exchanger performance.	Test specific heat transfer geometries and materials to obtain accurate design data Test heat exchanger core to obtain end-to-end core performance
Variation or drift in surface geometry during processing leads to lower than predicted performance.	Characterize fin folding process with specific geometry, material condition, tooling and process parameters. Test first and last product from run for heat transfer and friction characteristics. Schedule tool replacement to produce fin within acceptable geometric bounds
Structural weakness at orbital welds joining manifolds during loss of SHTS pressure event.	Employ a secondary structure to carry/share tensile load during event Reverse assignment of primary and secondary streams to assure compression on manifolds in all cases.
Weakness in fins or perimeter joints during loss of SHTS pressure event.	Over-pressure all cells as a condition of acceptance in processing Reverse assignment of primary and secondary streams to assure compression on cells in all cases.

Table 1-12 Unit-Cell Integration Options A-C

Option	Description	Figure
A	Two-Row, Primary Discharge Through Manifold System	
B	Single Row, Double-Length (2-m) Core, Individually-Manifolded	
C	Two-Row, Individually-Manifolded	

Options A, B and C are technical solutions for a single 510-MWth loop, and are consistent with the basic two-section series arrangement of vessels recommended in Reference 0 and shown in Figure 1-25. For each of these three options, the IHX is configured within two sections. The first section, designated as IHX-A, is a high-temperature and minimum-effectiveness heat exchanger constructed with a very high-temperature-capability alloy. The effectiveness/size of IHX-A is the minimum required to provide an acceptable operating temperature range for the second section, designated IHX-B. IHX-B is constructed with a medium-temperature-capable alloy and is used for the balance of the required thermal exchange between streams.

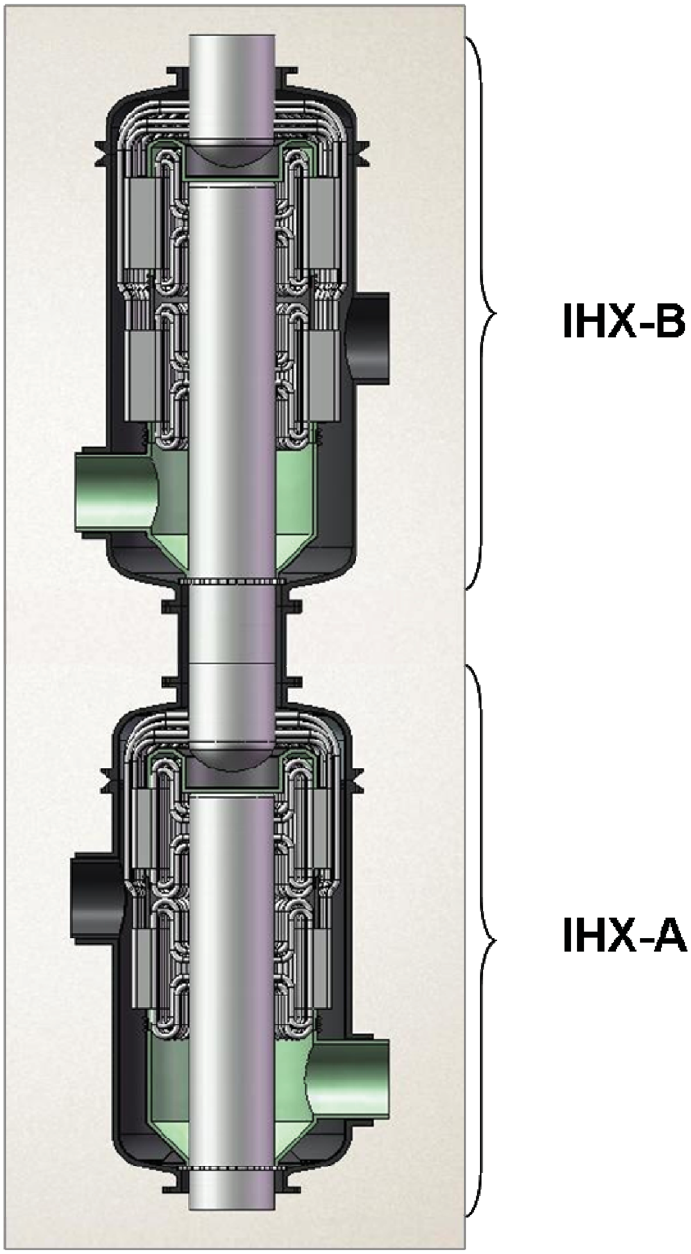


Figure 1-25 Series Arrangement of IHX Vessels for 510MWt

Consistent with the input functions and requirements of Section 1.2 and the corresponding HTS layout options of Section 1.3, configurations described in the following subsections place the PHTS penetrations on the centerlines of their respective vessels. SHTS penetrations are located through the sides of vessels creating consistency with the external piping insulation arrangement. To avoid redundant description, more comprehensive detail is provided for Option A, with subsequent configurations described in contrast.

1.4.2.1 Option A

Option A is one of two configurations employing two rows of cores. The most distinguishing feature of this integration scheme is the use of a headering arrangement for the internal pass (PHTS stream).

IHX-A is specified to provide the minimum thermal effectiveness needed to deliver gas at a temperature compatible with the material capabilities of Alloy 800H, specified for IHX-B. The outcome is that IHX-A is smaller than IHX-B as indicated by the cell dimensions of Section 1.4.1 and Table 1-13.

Table 1-13 Heat Exchanger Cores and Cells for IHX Option A

	IHX-A	IHX-B
Cell Count	25,270	35,230
Core Count	138	170
Core Stack Length, mm	1,000	1,000

Integration of the heat exchanger cores must take into account differential thermal growth rates of connected structures as well as plumbing of gases. The very high temperatures and temperature-differences specified for this metallic IHX demand that thermal displacements be carefully accounted for in a mechanical design. In Option A, the hot primary-inlet side of the assembly is mounted to the primary-inlet pipe header, and the cooler primary outlet side is mounted to the primary outlet pipe. With contiguous piping between these hot and cool structural regions, differential radial and axial displacements are reconciled by features intended to deflect with sufficiently low stresses to avoid unacceptable fatigue or creep-fatigue damage.

A cross-sectional layout of Option A can be seen in Figure 1-26, with important features of the design labeled. The basic functions and requirements of these features are presented here in Table 1-14.

Table 1-14 Basic Functions and Requirements for Option A

	Basic Functions	Special Requirements
Vessel	Contain internal pressure Locate and mount heat exchange assembly	Receive and expel gas streams Wall temperatures below 371˚C
PHTS Inlet Header Pipe	Mount hot-primary components Distribute PHTS gas to heat-exchanger cores	Sustain primary-atmospheric pressure differential for loss-of-secondary pressure event at 950˚C
Hot Flex Pipes	Convey PHTS flow between header and heat exchanger cores	Absorb radial differential displacement between cores and PHTS inlet header pipe Survive a minimum of 600 start-stop cycles
Heat Exchanger Cores	Transfer heat from PHTS to SHTS stream	Very low (TBD) leakage Sustain primary-atmospheric pressure differential for loss-of-secondary pressure event at 950˚C
Ring Manifold	Receive cooled PHTS stream from heat exchanger cores Deliver flow to riser pipes Constrain radial growth of core-array	Sustain primary-atmospheric pressure differential for loss-of-secondary pressure event at (TBD)˚C
Pressure-Compensated Riser Pipes	Convey PHTS stream from ring manifold to PHTS outlet header	Absorb axial differential thermal displacement between the ring-manifold and PHTS outlet header.
PHTS Outlet Header	Convey flow from riser pipes and through vessel wall. Support riser-pipes	Sustain primary-atmospheric pressure differential for loss-of-secondary pressure event at (TBD)˚C
SHTS Inlet	Deliver SHTS stream to the vessel	Design strategy consistent with piping and vessel
SHTS collector plenum	Receive heated SHTS stream from heat exchanger cores Deliver stream to discharge pipe	Absorb thermomechanical strain between cores and vessel

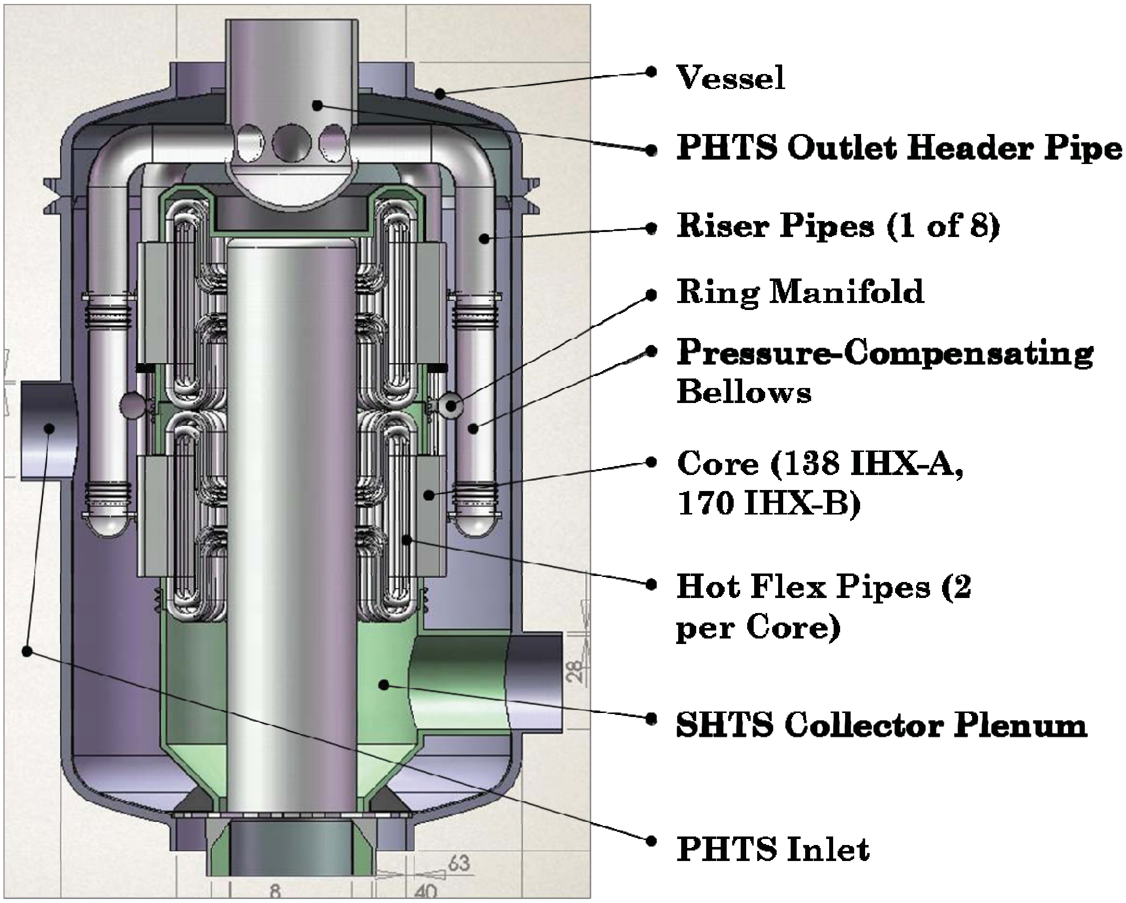
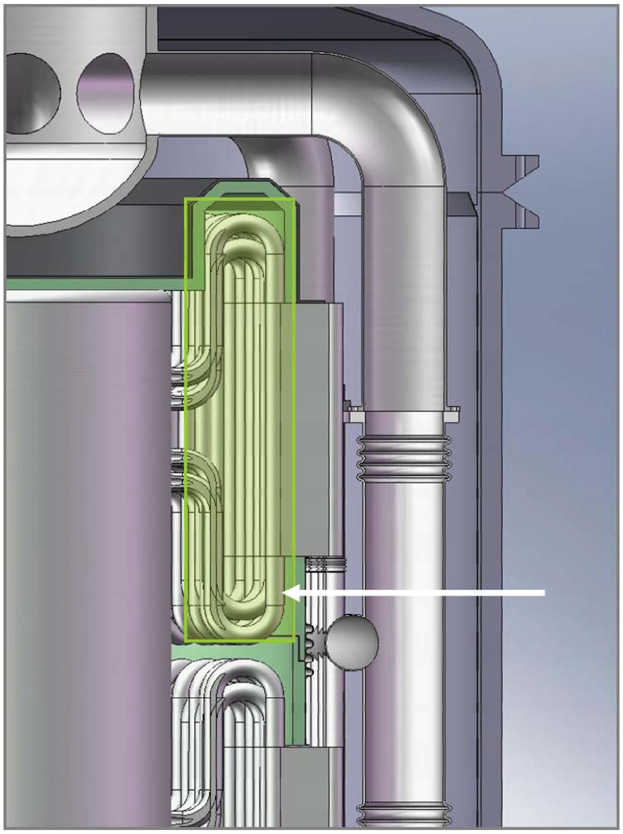


Figure 1-26 Unit-Cell IHX-A for Option A with Features Indicated

More detailed design data for Option A are presented in the following annotated figures.

The hot flex pipes (Figure 1-27) convey primary gas from the inlet header to the cores. By using two per core, gas maldistribution associated with a high flow is mitigated, while still allowing the tubes to be of smaller diameter, a feature that improves bending compliance. With the radial position of the outer (discharge) manifolds of the cores held by the ring manifold, the inward thermal displacement of the inlet manifold (-) and outward displacement of the inlet header (+) is accommodated by flexure of these pipes. Creating compliance lessens stresses and improves the ability of the structure to withstand the requisite start-stop cycles.



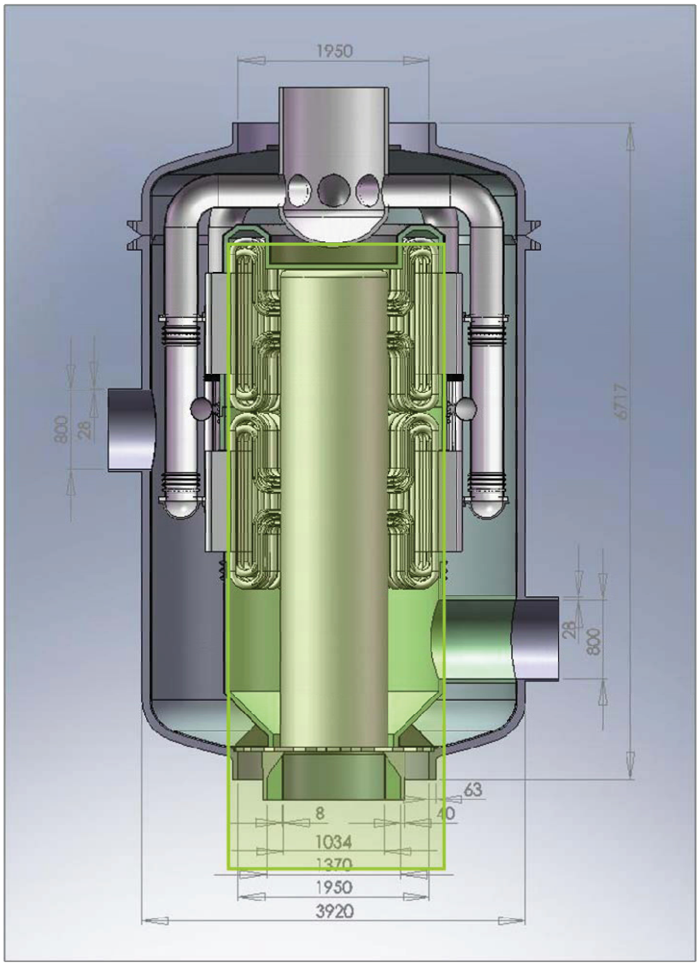
Hot Flex Pipe

- Alloy 617
- **Same design parameters as Primary** Supply Pipc
- **Standard tube sizing: 75 mm**
- *I.D.:* 63 mm
- **Wall Thickness, *t*: 6 mm**
- **Geometry accommodates relative thermal displacements**
- **Staggered layout prevents pipe** interference
- **Bend radius optimized to reduce** head losses

$$K \approx 0.25 \text{ for } r/D \approx 2$$

Figure 1-27 Design Notes for Hot Flex-Pipes

The PHTS header pipe (Figure 1-28) supports the cores and primary plumbing through the ring-manifold and lower legs of the riser pipes. With a 950°C operating temperature (IHX-A), this header is constructed using high-strength nickel superalloy. The 88-millimeter wall thickness is intended to provide a minimum 100-hour creep-rupture life in the event of a complete loss of secondary pressure. Given the 371°C temperature limit of the vessel, the penetrations for both IHX-A and B, involving this header, are actively cooled as specified by Functions and Requirements, Section 1.2.



PHTS Inlet Header Pipe

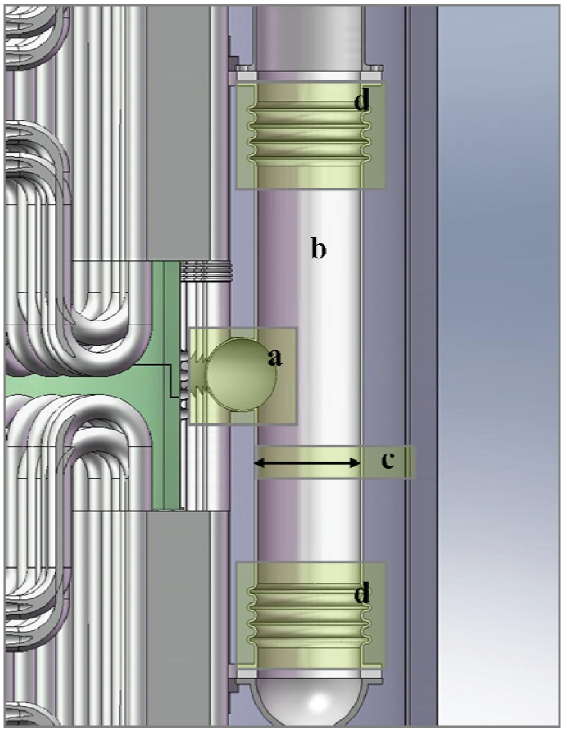
- Alloy 617
- **Designed for Maximum Pressure Difference 9 MPa**
- **Rupture Strength (σ) 950 °C,** 100h ≈55 MPa
- I.D.: 1,034 mm
- **Wall Thickness, *t*: 88 mm**

$$\sigma = P(I.D.)/2t$$

Figure 1-28 Design Data for PHTS Inlet-Header Pipe

The ring manifold and pressure-compensated riser pipes deliver flow from the heat exchanger cores to the PHTS discharge header. This piping detail establishes the radial position of the heat exchanger cores while allowing vertical (axial) mechanical compliance. The ring manifold, its temperature controlled by cooled PHTS gas, operates at a relatively low temperature (760˚C). As a complete hoop, it reacts the mechanical spring force from the inwardly deflected hot flex-pipes, on the inboard side of the cores. Yet, its axial position is controlled by the primary inlet header, via the flex-pipes, as the primary inlet header grows to its displaced operating dimensions. The primary discharge header fixed to the top of the vessel controls the axial position of the upper end of the riser pipes.

With the lower section of the riser pipes welded to the ring-manifold, the differential thermal displacement between the ring manifold and the upper leg of the riser-pipe is absorbed by axial deflection of the compensating bellows as seen in Figure 1-29. Hydraulic pressure exerted on the end-cap at the lower terminus of the riser-pipe is reacted by rods, indicated in Figure 1-30, tied to the upper leg. Loads applied to the ring manifold are thereby reduced to mechanical deflection of the bellows, a spring force.



Ring Manifold and Pressure Compensated Riser Pipes

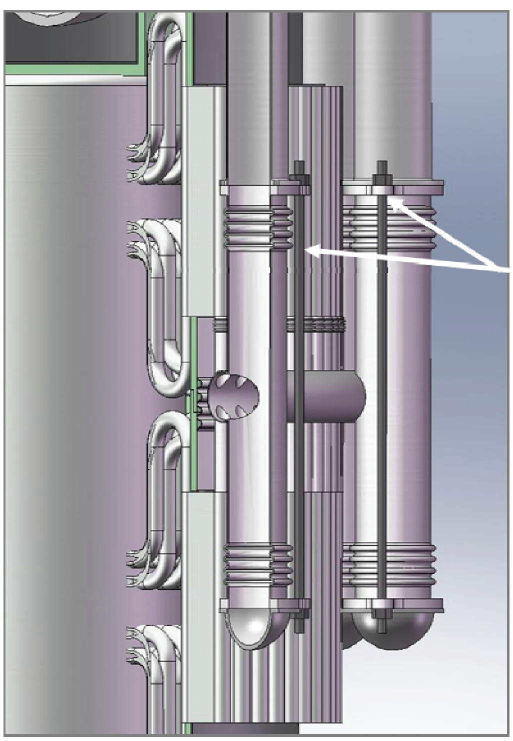
a. Ring Manifold I.D.: 223 mm

b. (8) pressure-compensated Riser Pipes connect Ring Manifold to Primary Discharge Header

c. Leg Riser diameter: 320 mm

d. Bellows above and below Ring Manifold allows independent axial displacement between Ring Manifold and Primary Discharge Header

Figure 1-29 Design Notes for Ring-Manifold Collector



Tie-Rods

- Alloy 625
- Two Threaded Tie-Rods per Leg
- Tie-Rod Diameter: 35 mm
365 kN Tensile Force Per Rod
- Leg Flange Thickness, t: 45 mm
Bending Stress

$$\sigma = Mt/2I$$

Figure 1-30 Design Notes for Tie-Rods Reacting Hydraulic Loads for Pressure-Compensating Riser Pipes

Secondary seals are a system of light-gauge structures employed to force SHTS flow through the counterflow matrices of the heat-exchanger cores. The principal technical challenge to designing this system is accommodation of component displacement without opening leakage paths. The differential pressure created by frictional loss through the cores is used to advantage in maintaining minimum bypass leakage around the cores. Design notes for secondary seals are provided in Figure 1-31.

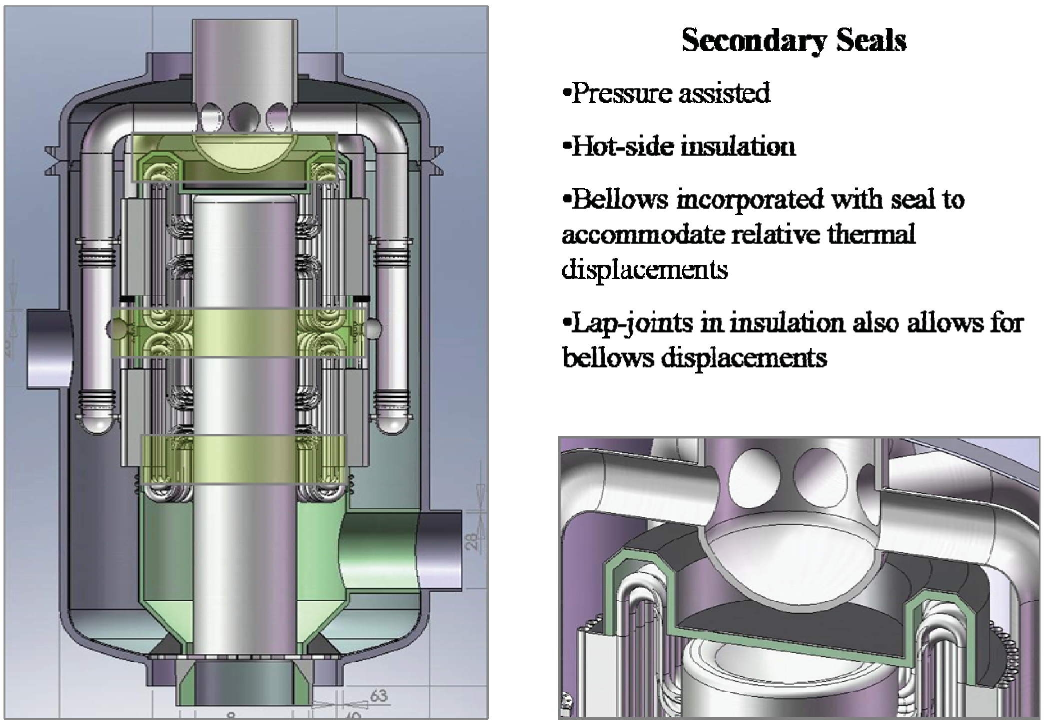


Figure 1-31 Design Notes for Secondary Seals

Secondary seals and their integration with the cores can be seen in the series of figures that follow. Figure 1-32 presents a segment of the seal assembly at the top of a row of cores. What is labeled “diaphragm seal” is a continuous full-hoop structure. The annular sheet at the top is intended to act as a diaphragm to provide axial compliance in a simple form. It is attached rigidly to the core end seals which are, in-turn, rigidly joined to their cores. Intercore seals, assisted by the differential pressure through the external pass through the cores, bear against edge seals attached directly to the cores. This arrangement provides a flexible structure to follow the cores as they are displaced by thermal growth in the transition from its room-temperature state to its operating state.

Edge seals are required to adapt the ribbed detail of the core to a flat surface. In Figure 1-33, it can be seen how edge seals fit over the edge of cells in the core. The first vertical row of edge seals creates a wall. With the inter-core seal bearing against it the external stream is forced through the cores. Successive rows contain flow within the external side of the core, and provide redundancy in the event of leakage past the first row.

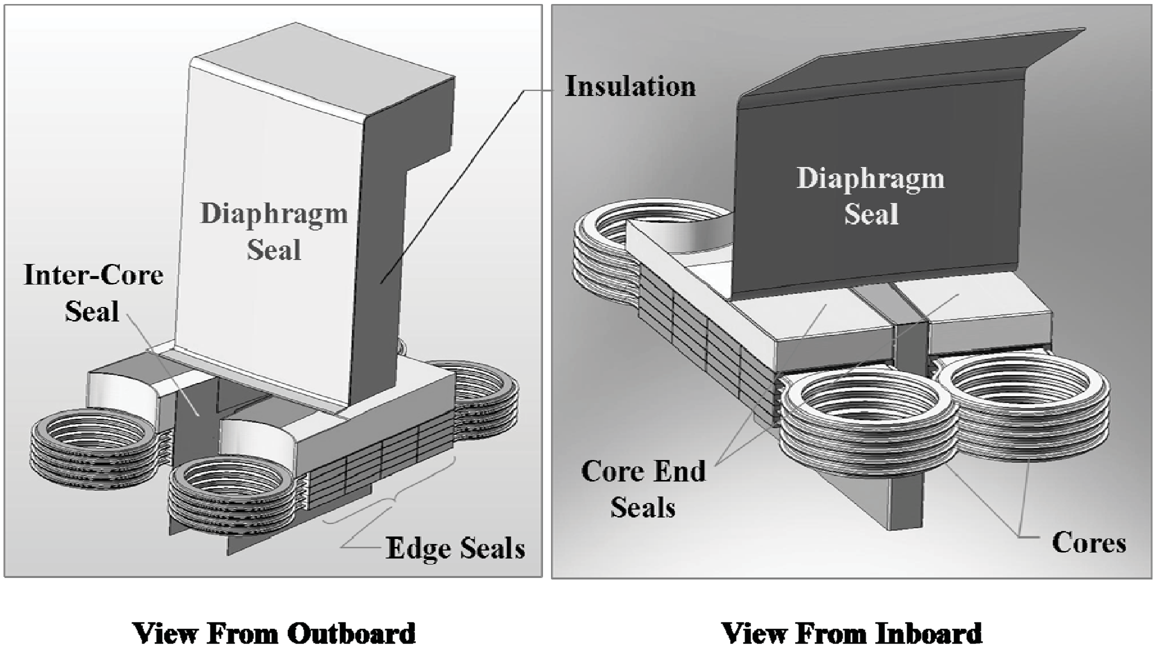


Figure 1-32 Secondary Seal Assembly Segment

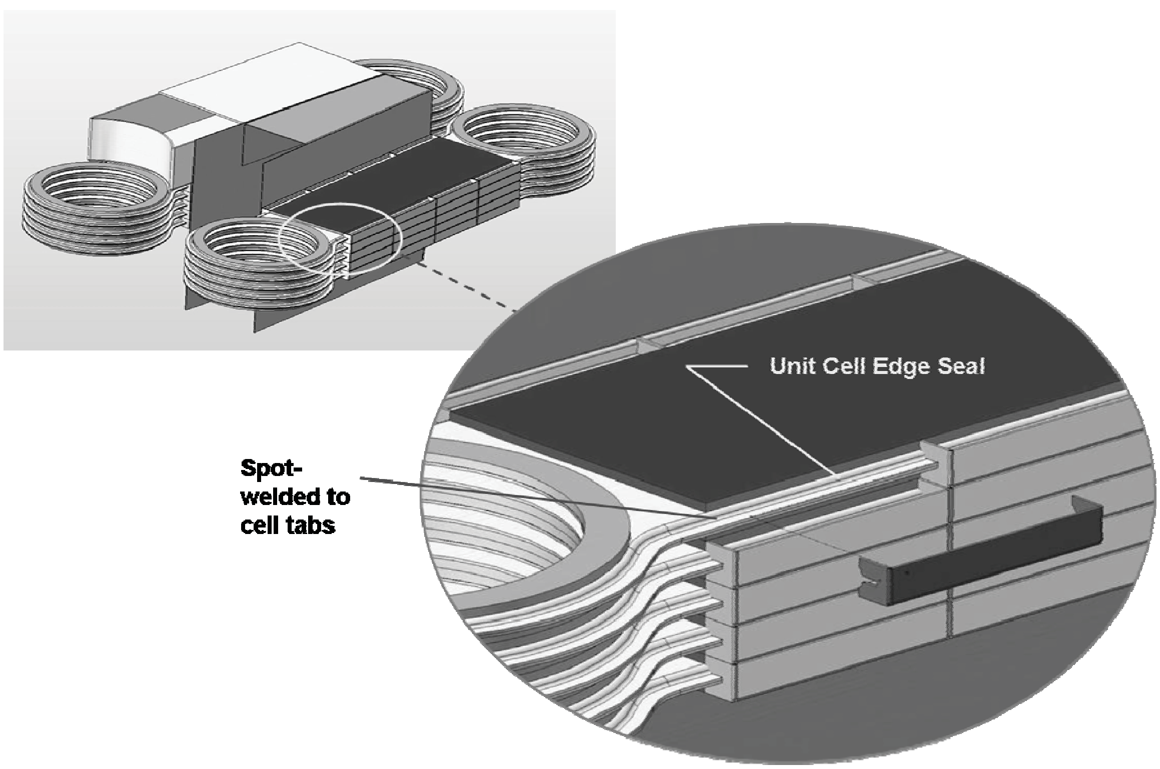


Figure 1-33 Secondary Seal Edge Detail

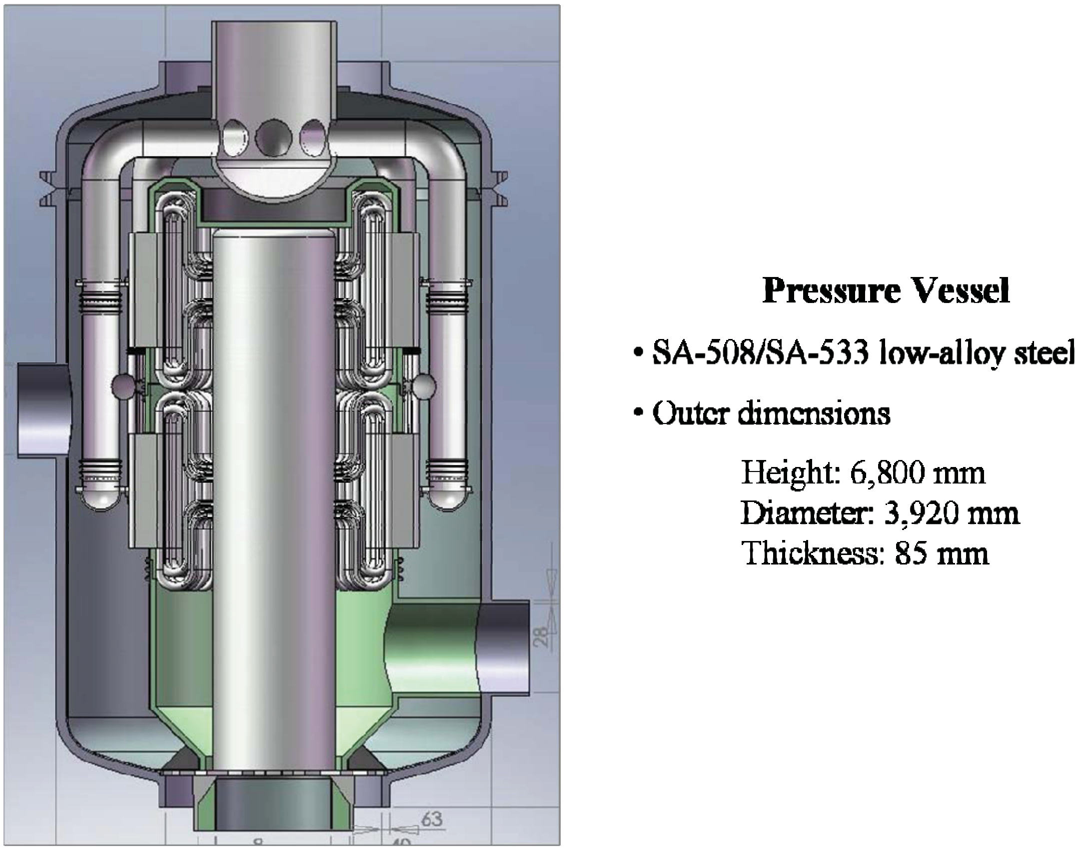


Figure 1-34 Design Notes for Option-A IHX Pressure Vessel

Hotter gases (PHTS inlet and SHTS outlet) are confined to the inner regions of the vessels (Figure 1-34), with cooler gases nominally outboard. The cooled gas, SHTS inlet, wets the inner surface of the IHX-B vessel to manage vessel-wall temperatures.

Primary (PHTS) flow enters each vessel through the bottom via the inlet header pipe and is distributed through pairs of serpentine pipes into each core, as shown in Figure 1-35. These pipes are shaped to create structural compliance to accommodate differential thermal growth between hot and cool structures. Cooled gas exiting all cores flows into a ring manifold located between the two rows of cores, and delivers flow into eight pressure-compensated riser pipes that empty at the top of the vessels into a discharge header pipe.

Secondary flow enters through a single penetration in the side of each vessel and distributes into the annular space between the vessel and cores. This is shown in Figure 1-35. Gas flows radially inward through the cores as insisted by seals located between cores and adjacent structures above and below. Exiting the cores, the heated SHTS gas flows downward in the annular space between cores and the primary-inlet header pipe and into a plenum below the core-array. Exiting the plenum, heated secondary gas passes through an insulated penetration in the side of each vessel. From IHX-B, gas is directed to IHX-A for further heating. From IHX-A 900°C, gas is fed into SHTS piping as process heat.

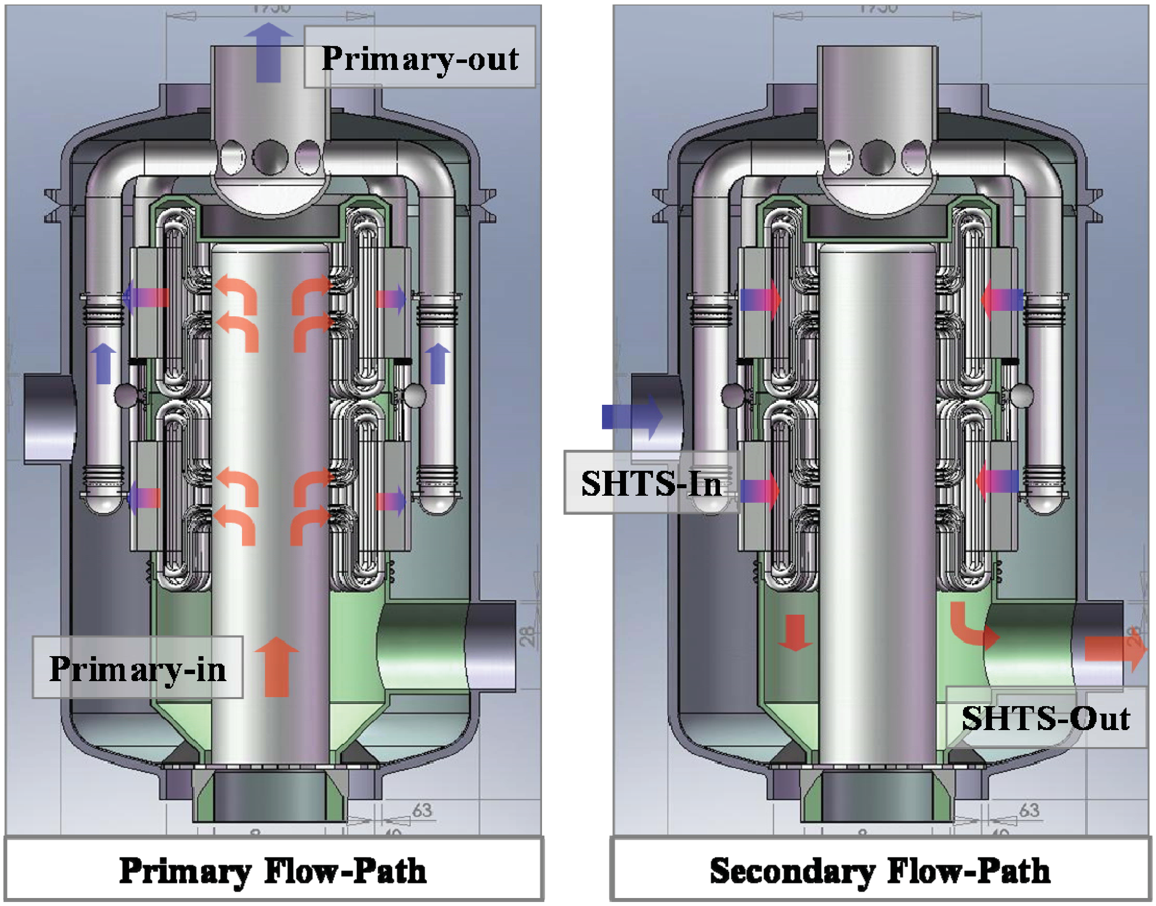


Figure 1-35 Flow Paths through IHX Option A

The basic physical dimensions of Option A, IHX-A, are shown in Figure 1-36. The flange-to-flange axial length is 6.7-meters and the outer diameter is 3.9-meters. IHX-B will be approximately 290-mm larger in diameter due to the greater counterflow length of the heat exchanger cores – 300-mm, versus 155-mm for IHX-A.

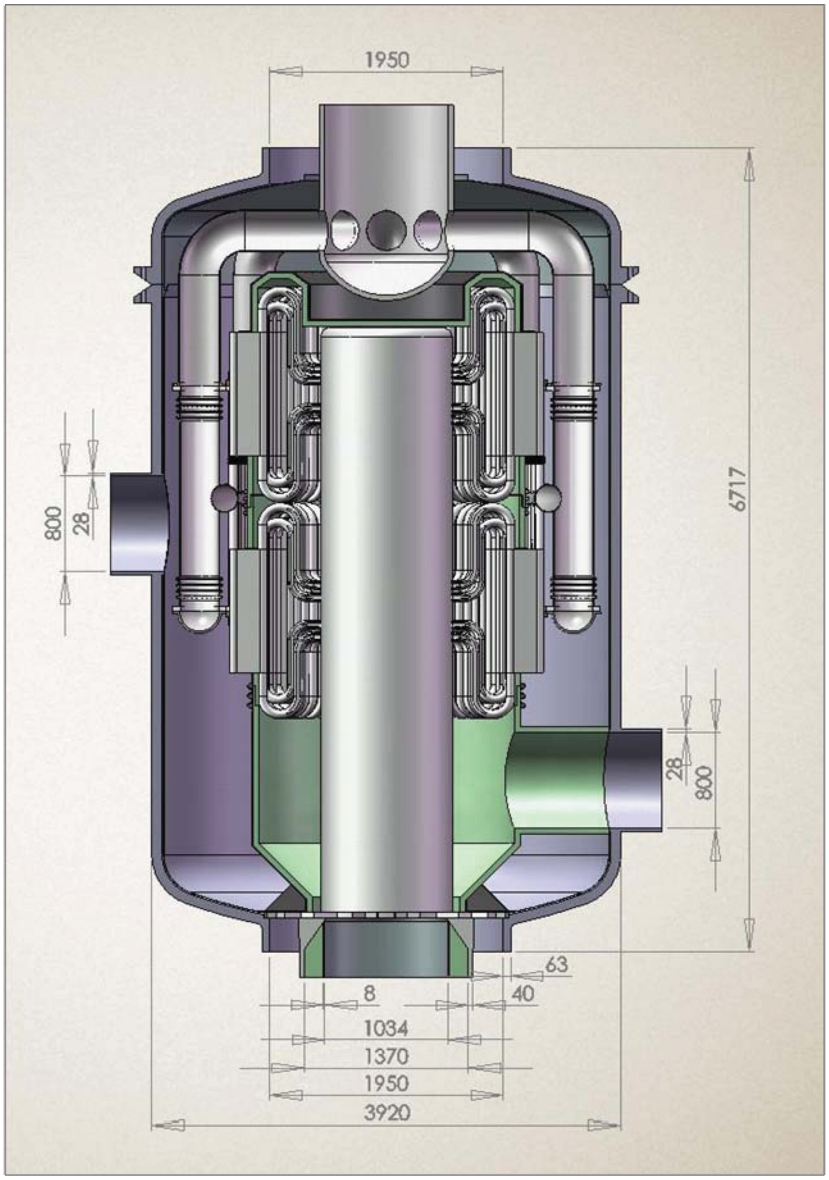


Figure 1-36 Dimensioned Cross Section of Option A IHX-A Assembly

1.4.2.2 Option B

To reduce the number of welded connections and increase the overall compliance of piping, a single row of two-meter-tall cores was conceived. Shown in Figure 1-37, the IHX-A rendering of Option B is presented in cross-section with salient features indicated.

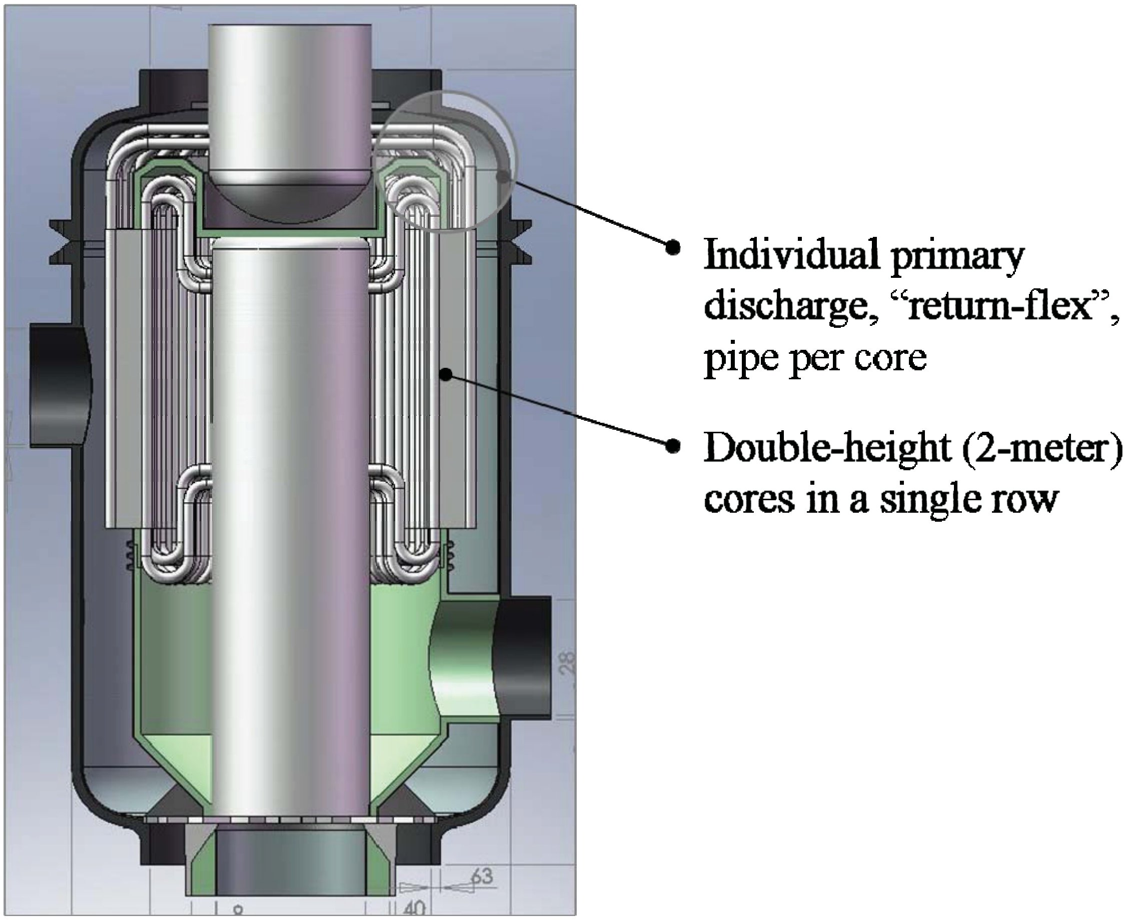


Figure 1-37 Option B (IHX-A Shown) with Features Annotated

The double-height of the core, while simplifying the plumbing arrangement, presents technical risk with respect to flow-distribution in the core (and attendant ineffectiveness) and overall primary pressure loss. With the full compliment flow received by two one-meter cores through the same manifold openings, gas velocities are doubled, depressing the dynamic term of the static-pressure by a factor of eight. Since flow through the core is a function of the static-pressure-difference between manifolds, this acceleration at the terminal planes requires evaluation and likely some mitigation before it could be recommended. And with pressure loss generally tracking with dynamic pressure for a broad range of Reynolds numbers, losses associated with the inlet and outlet piping will be greater than with a two-row solution.

Primary-return "flex-pipes" are employed to plumb each core to the primary discharge header. This feature, shown in Figure 1-38, provides a source of axial and radial compliance to resolve differential thermal displacements. They also provide a means of accessing individual cores and their respective plumbing to specific ports in the headers for leak testing and, if necessary, isolation by plugging the inlet an outlet headers.

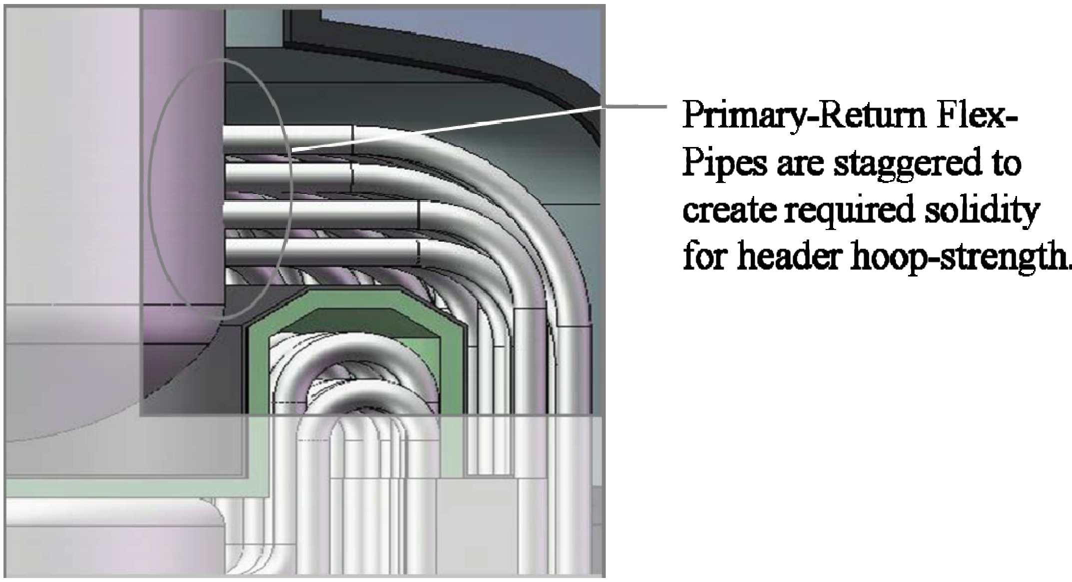


Figure 1-38 Primary-Return "Flex-Pipes"

Overall dimensions are provided for Option B in a rendering of the IHX-A section in Figure 1-39. At 5.5-meters length and 3-meters diameter, this configuration is smaller than Option A.

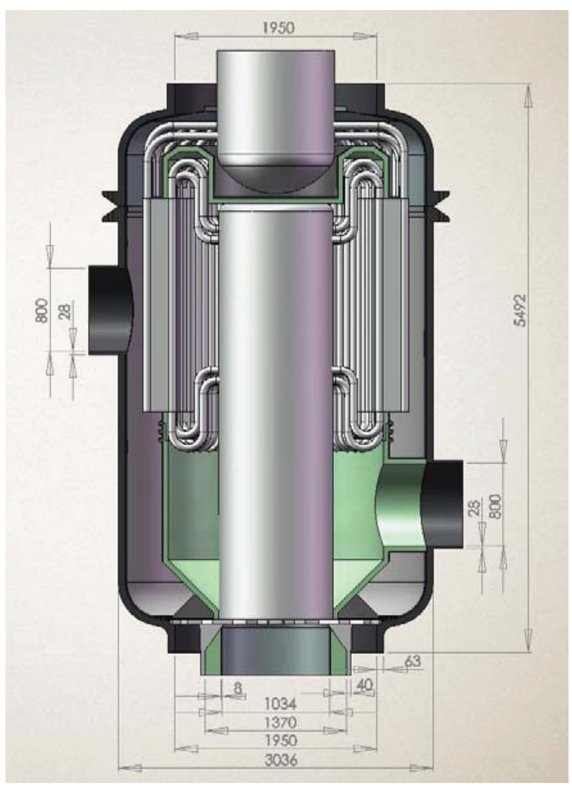


Figure 1-39 Basic Dimensions for Option B (IHX-A Shown)

1.4.2.3 Option C

Sharing the general architecture of Option B, but returning to the two-row arrangement of Option A, Option C avoids pit-falls of both while retaining their essential virtues. Seen in Figure 1-40, primary-return "flex-pipes" plumbed to individual cores are borrowed from Option A to provide thermal strain-relief and allow leak isolation to the heat-exchanger core level. At one-meter, the core heights suggest little concern for the performance-degrading effects of maldistribution.

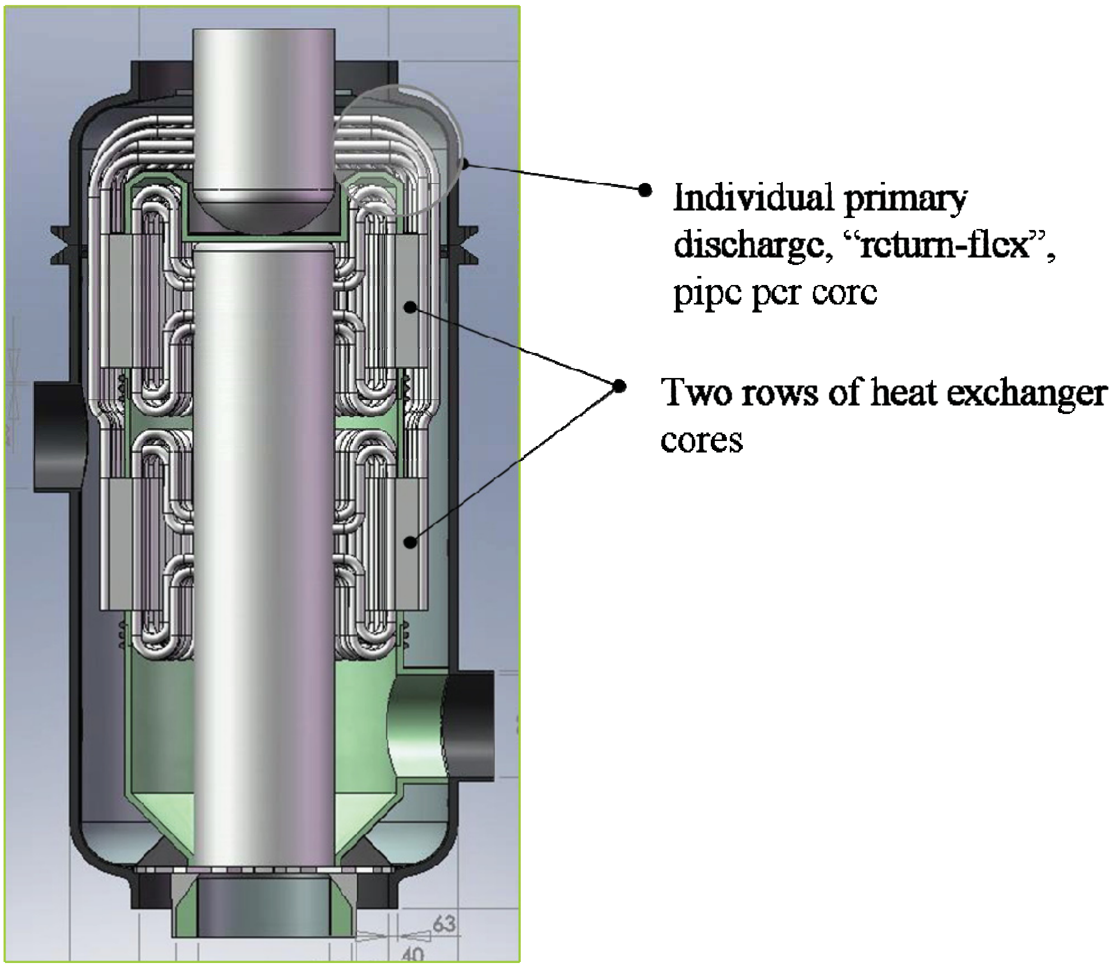
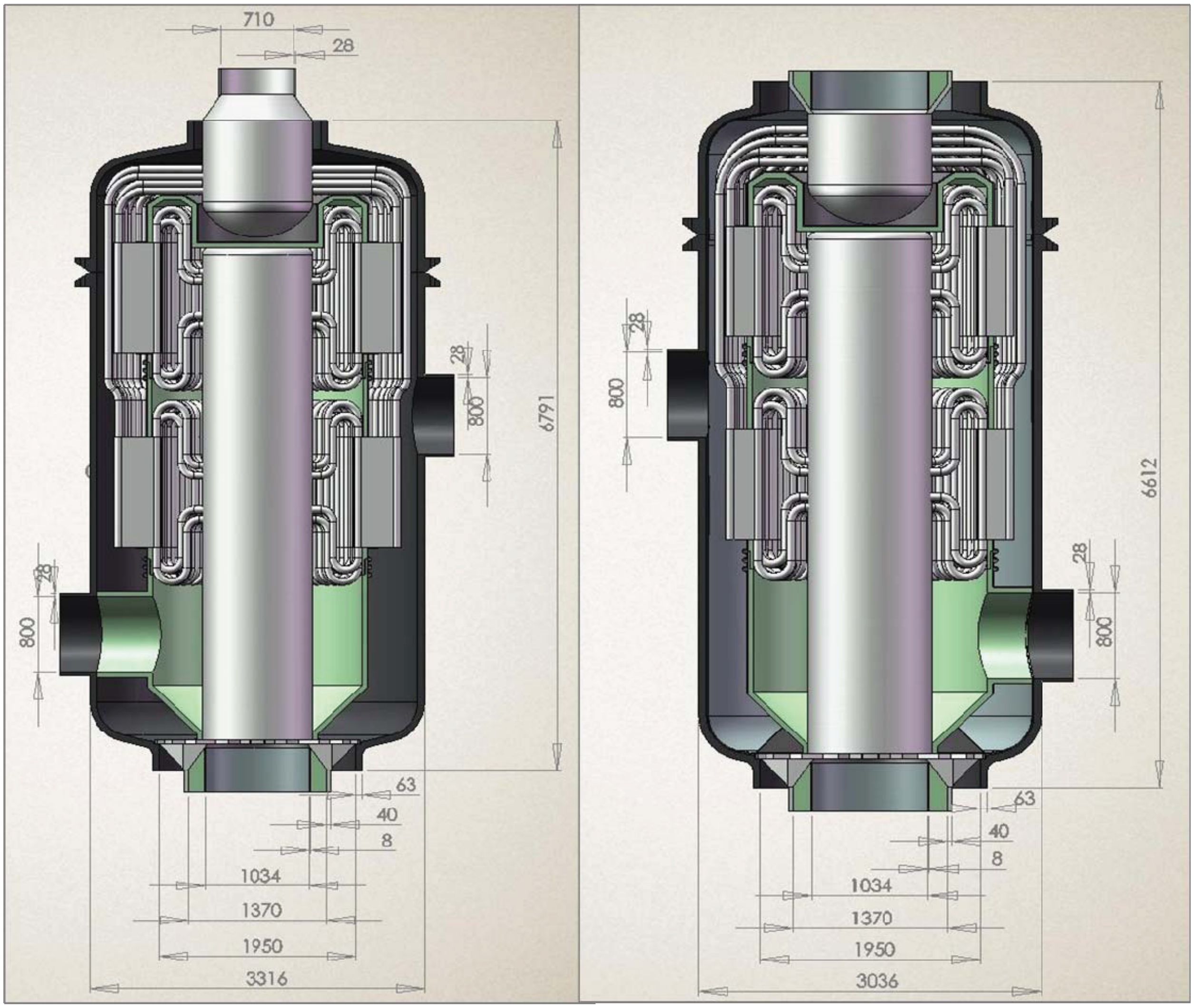


Figure 1-40 Option C Differentiating Features (IHX-A Shown)

Dimensions for Option C as a complete IHX, and with greater detail for IHX-A, are shown in Figure 1-41.



Option C IHX-B **Option C IHX-A**

Figure 1-41 Option C IHX-A/IHX-B Assembly and IHX-A Detail

1.5 Involute IHX

The involute-tube IHX is a unique variation within the general class of tube-shell heat exchangers. It is included in this study because of its potential for high performance and for a natural flexibility to mitigate potentially damaging thermal strain. Its performance potential is derived from the many-pass-crossflow-overall-counterflow relative flow orientation of the two streams created by heat-transfer tubes spiraling between concentric tube-sheets. It is this involute trajectory of each tube, shown in Figure 1-42, that suggests flexibility to resolve differential thermal growth with modest mechanical strain.

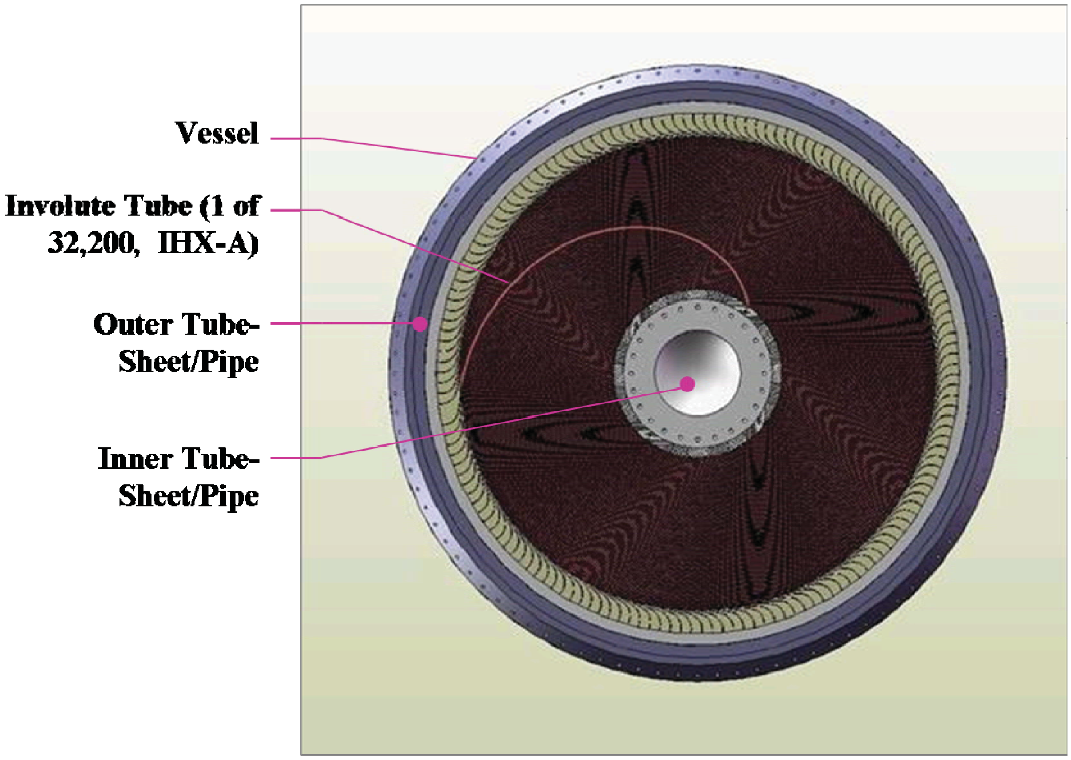


Figure 1-42 Involute IHX Features (Top View)

Various size externally-finned tubes with smooth bores, and with internal fins, were investigated focusing on performance and overall packaging volume. External fins are specified to be hexagonal 0.5 mm-thick plates bonded to the outer tube diameter on a 0.08 mm pitch. Their minimum radial dimension from the tube outer diameter was specified to be 1.5 diameters. An example of a sectioned tube is presented in Figure 1-43 along with a view of the interface between the tubes and inner tube-sheet. The hexagonal outline of fins allows close packing of this secondary surface. The particular example shown in this figure has internal fins captured between concentric tubes.

Note that the radial space between the tube-sheet and the red-shaded fins of the heat-exchange matrix provides volume for the distribution of the incoming primary stream.

Flow distribution headers, with the exception of the secondary (internal tube flow) outlet are annuli. From the inside, out, Figure 1-44 and Figure 1-45 show these features as follows:

- Secondary Outlet – internal to the central pipe
- Primary Inlet – between the central pipe and the inner edge of the heat-exchange matrix
- Primary Outlet – between the outer edge of the heat exchange matrix and the inner diameter of the outer tube-sheet/pipe
- Secondary Inlet – between the outer diameter of the outer tube-sheet/pipe and the inner diameter of the vessel

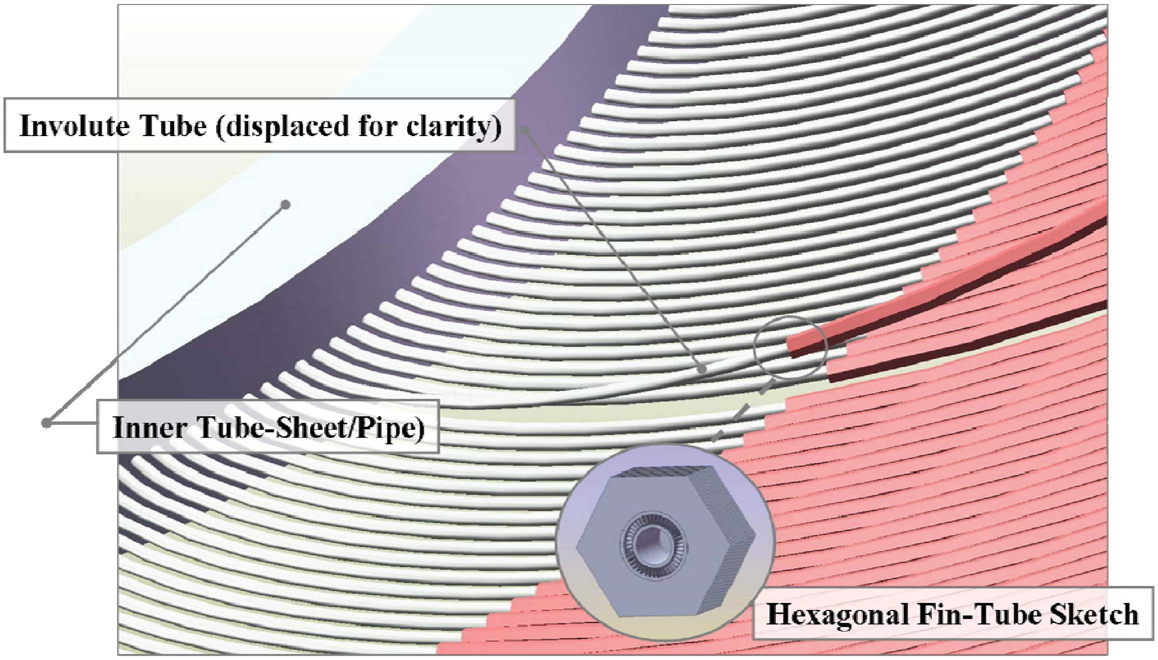


Figure 1-43 Involute-Tube/Inner-Tube-Sheet Detail

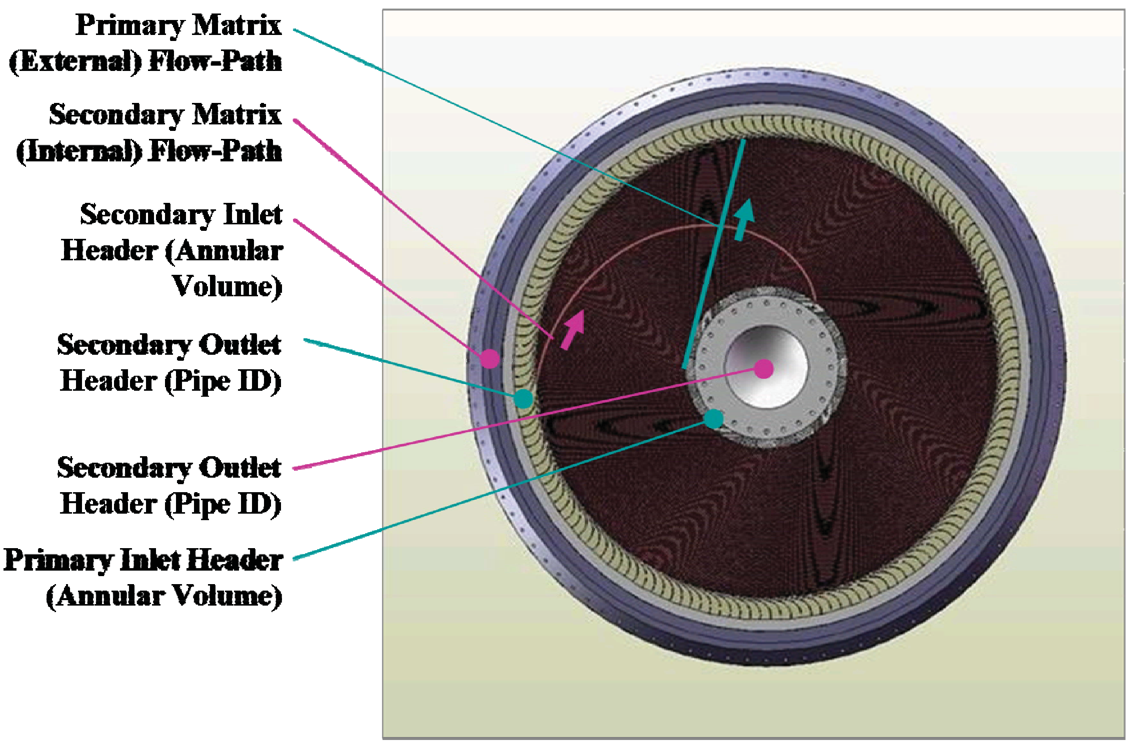


Figure 1-44 Involute IHX Headers (End View)

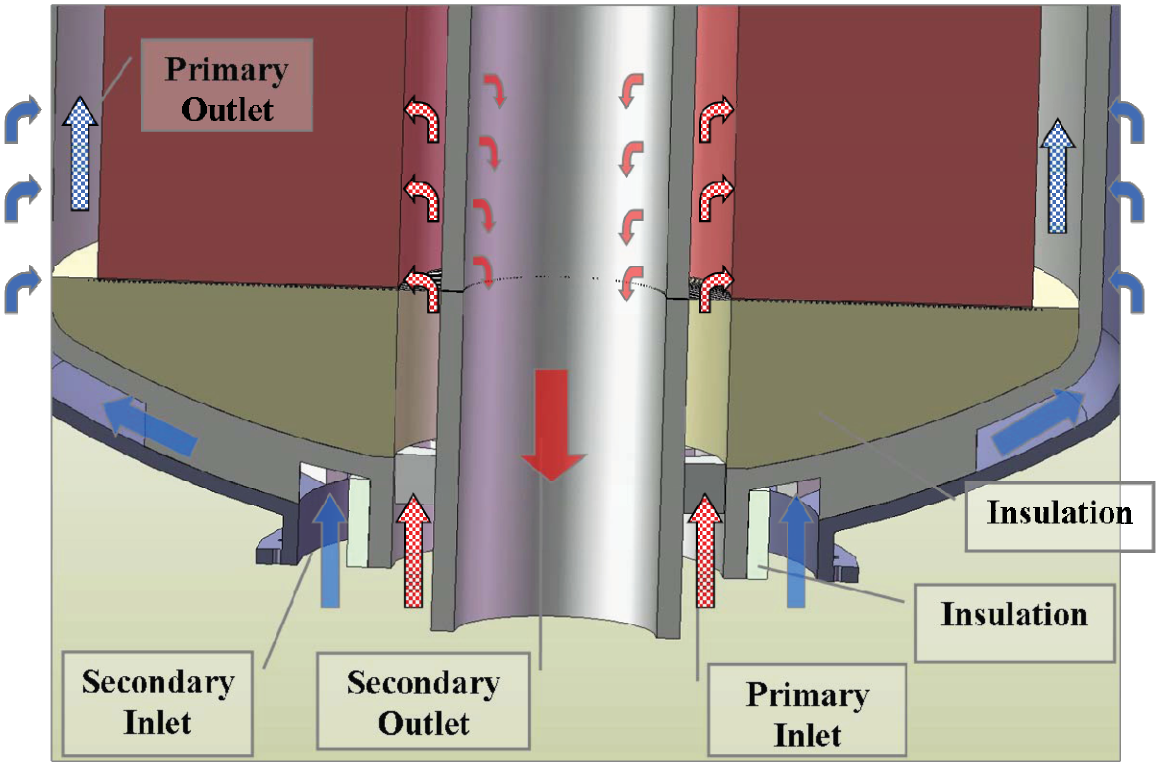


Figure 1-45 Involute IHX Headers (Lower Detail)

Flow through the heat-exchange matrix is also indicated in Figure 1-44. The secondary (SHTS coupled) stream distributes into, and flows through, the array of 32,200 tubes in IHX-A while the primary (PHTS-coupled) flows outward over the tubes on tangential streamlines. These relative paths create the nearly pure counterflow conditions favorable to highly effective heat exchange in what is, from inspection, clearly a crossflow heat exchanger.

The Core Outlet Pipe HGD requires external cooling which by definition implies a co-axial IHX-A inlet pipe. It is hence preferred (see Functions and Requirements) that the IHX PHTS inlet pipe not be combined with SHTS piping to form a tri-axial pipe. With the assumed assignment of the secondary pass to the inside of the tubes, it follows that it must discharge through the central pipe. This is not consistent with the stated preference for a side-discharge from the vessel (to allow single HGD entry). Because the SHTS and PHTS flows are balanced, however, reversal of this assignment would create the opportunity to collect flow below the heat exchange matrix and direct it through the cylindrical wall of the vessel. The only substantive implication is the direction of pressure loading on the tubes. If coupling assignments are reversed, and the shell-side is coupled to the SHTS, the nominally higher SHTS pressure then loads tube-to-tube-sheet welds in an unfavorable direction. This may be a minor consideration given the low magnitude of that differential-pressure during normal operation and the low number of start-stop cycles specified. There is however a benefit in the event that SHTS pressure is lost. The high attendant internal pressure in that event will tend to compress the back of the tube-to-tube-sheet weld, a favorable loading condition.

The central tube-sheet/pipe and the outer tube-sheet/pipe may be required to withstand a high differential pressure in the event of a loss of secondary pressure. Wall thicknesses are sized accordingly. Regardless of the assignment of primary and secondary streams, wall thicknesses are substantial.

The involute IHX, as presently configured, is not appropriate for an IHX-B, primarily due to limitations in fin efficiency. The diameter of the heat exchanger becomes simply too large to be practical. This is discussed in more detail in Section 1.8.2. At the end of that section foam-metal is discussed as an alternative to the fins prescribed in the present design. With its greater β-ratio (area/volume) that surface may provide the compactness needed to achieve viability.

1.6 Assessment and Selection

This section evaluates the three counter-flow-plate-fin IHX options described in Section 1.4, together with the shell-and-tube option described in Section 1.5. It has been assumed that the IHX is connected on the core and shell-sides, respectively, to a single PHTS and SHTS loop. The PHTS and SHTS are essentially pressure balanced, with slight bias from the SHTS to the PHTS. A further common feature of these IHX designs is the split into high (IHX-A) and low temperature (IHX-B) sections and the enclosing of each section in a separate pressure vessel. The two pressure vessels are connected in series.

The two types of heat exchange cores that have been considered in this assessment are a compact counter-flow-plate-fin core design that includes several stacks of narrow aspect ratio "unit cells" connected by welded manifold rings (options A, B and C) and a compact cross-flow shell-tube core design with an involute finned tube bundle.

The major differences among the four options considered are:

- Option A – Two rows of unit cell cores with the outlets on the core-side connected to a manifold system.
- Option B – Single row of double height unit cell cores with the outlets on the core-side individually manifolded to allow detection and isolation of leaks in the PHTS/SHTS pressure boundary.
- Option C – Two rows of unit cell cores with the outlets on the core-side individually manifolded (upper and lower rows connected in series) to allow detection and isolation of leaks in the PHTS/SHTS pressure boundary.
- Involute – Single involute rotated shell-tube core with a radial matrix flow.

The key features of these four IHX options are summarized in Table 1-15. Note the difference in mass of the IHX based on the involute design with respect the IHXs based on the plate-fin design.

Table 1-15 Key Features of Four Single-Loop IHX Options

Attribute	Option A	Option B	Option C	Involute
Type of core	Compact plate/fin	Compact plate/fin	Compact plate/fin	Compact shell & tube
Type of heat exchange single cell or tube	Unit-cell with brazed fins	Unit-cell with brazed fins	Unit-cell with brazed fins	Involute tube with external brazed fins
Number of Unit Cells (A,B,C) or tubes per core stack (Involute)	25,270 (IHX-*A*) / 35,230 (IHX-*B*)	25,270 (IHX-*A*) / 35,230 (IHX-*B*)	25,270 (IHX-*A*) / 35,230 (IHX-*B*)	33,600 (IHX-*A*) / 36,240 (IHX-*B*)
Method of connecting single unit cells or tubes to form core stack	Inlet/outlet ring segments of individual unit cells connected to form manifold	Inlet/outlet ring segments of individual unit cells connected to form manifold	Inlet/outlet ring segments of individual unit cells connected to form manifold	Tubes welded to inner and outer tube sheets
PHTS coolant flow	Inside pressure boundary parting sheets	Inside pressure boundary parting sheets	Inside pressure boundary parting sheets	Inside the tubes
SHTS coolant flow	Outside pressure boundary parting sheets	Outside pressure boundary parting sheets	Outside pressure boundary parting sheets	Outside the tubes
Coolant flows	Counter flow	Counter flow	Counter flow	Cross counter flow
Number of core stacks of heat exchange single cell	138 (IHX-A) /170 (IHX-B)	69 (IHX-A) /85 (IHX-B)	138 (IHX-A) /170 (IHX-B)	One per vessel
Mass of IHX[1], kg	11,000	11,000	11,000	300,000[2]
Core stacks layout	Cores arranged in two rows	Cores arranged in a single row	Cores arranged in two rows	Cores arranged in a single row
PHTS discharge arrangement	All the core stacks feed into eight manifolds	Each core stack is individually manifolded	Each core stack is individually manifolded (upper and lower rows connected in series)	Core-side discharge through an outer shroud

[1] Mass includes IHX-A and IHX-B
[2] The weight is driven by the external fin mass. Use of a foam-metal can reduce this mass to 45,000 Kg.

These four IHX options have been compared against each other in Table 1-16. The objective of the comparison was to select a preferred IHX configuration for the single-loop, 510MWt configuration. The selected configuration will be further evaluated in Section 3.5 in terms of system-level layout, along with other options for parallel and multi-loop architectures that are described in Section 1.7.

The results of the present evaluation are summarized in Table 1-16. It should be noted that the evaluation and comparison are qualitative only; engineering judgment and consultation among experts were the bases for comparing the respective options. It should also be noted that the comparison was based on the available IHX designs that are, at this point, only conceptual in nature. The evaluation was conducted in the framework of five categories that describe different aspects of the IHX design:

- Design/Technology Development
- Manufacturing and Transportability
- Operation and Maintenance
- Safety and Investment Protection
- Lifecycle Cost

Each of these five categories was further divided into sub-categories to evaluate different aspects of the design. One sub-category that appears throughout is a comparison of the risks that this project will incur by introducing an IHX that must operate in a nuclear environment.

A color code has been used to highlight the relative advantages **(green)** and relative disadvantages **(red)**. When a design feature has the same relative advantage or disadvantage for all four options, a **black** color was used.

Several assumptions had to be made in order to create a level playing field for a fair comparison. These are identified at the top of Table 1-16.

Table 1-16 Detailed Comparison of IHX Options A, B, C and Involute

Consideration	Option A Two Rows, Primary Discharge Through Manifold System	Option B Single Row, Double Length Cores Individually Manifolded	Option C Two Rows, Primary Discharge Trough Individual Manifolds	Involute Compact Shell-Tube with External Brazed Fins
Assumptions 1. PHTS and SHTS are closed pressurized helium loops, nominally pressure balanced; with the SHTS at slightly higher pressure. 2. PHTS helium is on the core/tube-side. 3. In all four options, the IHX is split into high- (IHX-A) and low-temperature (IHX-B) sections. 4. No planned maintenance is required for the IHX during its design life. 5. In Options A, B and C, tubes connecting individual IHX cores to top/bottom ducts can be plugged via access to central ducts. 6. Alloy 617 is used for high-temperature components of IHX-A; Alloy 800H is used for high-temperature components of IHX B. **Color code : Relative Advantage / Disadvantage / Neutral**				
1.0 Design/Technology Development				
1.1 Similarity to DPP SSCs				
Individual cores and piping	No similarity.	No similarity.	No similarity.	No similarity.
Integration of cores within the pressure vessel	Some similarity with DPP recuperator.	Some similarity with DPP recuperator.	Some similarity with DPP recuperator.	No similarity.
1.2 Use of Developed Technologies				
Individual cores and piping	Brazed plate/fin technology has been extensively used. High temperature materials require development.	Brazed plate/fin technology has been extensively used. High temperature materials require development.	Brazed plate/fin technology has been extensively used. High temperature materials require development. .	Technology of shell & tube with external brazed fins is mature. Small diameter (< 6-mm) tubes with external or internal fins require development. Optimization of the external fin design for IHX-B requires testing. High temperature materials require development.

Table 1-16 Detailed Comparison of IHX Options A, B, C and Involute (cont'd)

Consideration	Option A Two Rows, Primary Discharge Through Manifold System	Option B Single Row, Double Length Cores Individually Manifolded	Option C Two Rows, Primary Discharge Trough Individual Manifolds	Involute Compact Shell-Tube with External Brazed Fins
Integration of cores within the pressure vessel	No new technology required. Sealing of the shell-side flow between cores requires new and complicated design.	No new technology required. Sealing of the shell-side flow between cores less complicated than A and C, but requires new and complicated design.	No new technology required. Sealing of the shell-side flow between cores requires new and complicated design.	The required IHX-B vessel diameter is larger than that specified in the requirements.
1.3 RISK - Design/ Technology Development				
Individual cores and piping	Applies proven plate-fin technology. New high-temperature design with potentially high loads from loss of SHTS pressure (LOSP). Differential thermal expansions and seismic loads are design concerns.	Applies proven plate-fin technology. New high-temperature design with potentially high loads from LOSP; simpler piping design than A and C. Differential thermal expansions and seismic loads are design concerns.	Applies proven plate-fin technology. New high-temperature design with potentially high loads from LOSP. Differential thermal expansions and seismic loads are design concerns.	Risky because there is no precedent for this design. Risky because of the need to fabricate a vessel with a diameter larger than 6 m. Risk of leakage due to large number of tube to tube-sheet welds.
Integration of cores within the pressure vessel	Complicated IHX core support design. IHX-A vessel walls require shrouds for forced cooling using IHX-B secondary inlet helium.	Less complicated IHX core support design than A and C because of the single row. IHX-A vessel walls require shrouds for forced cooling using IHX-B secondary inlet helium.	Complicated IHX core support design. IHX-A vessel walls require shrouds for forced cooling using IHX-B secondary inlet helium.	Simpler core support design. IHX-A vessel walls require shrouds for forced cooling using IHX-B secondary inlet helium.

Table 1-16 Detailed Comparison of IHX Options A, B, C and Involute (cont'd)

Consideration	Option A Two Rows, Primary Discharge Through Manifold System	Option B Single Row, Double Length Cores Individually Manifolded	Option C Two Rows, Primary Discharge Trough Individual Manifolds	Involute Compact Shell-Tube with External Brazed Fins
2.0 Manufacturing and Transportability				
2.1 Manufacturability and Constructability				
Individual cores and piping	Technology for manufacturing unit-cells is established. Requires a large number of welds to join unit-cells at the manifold ring segments to form cores. The fin folding process must be very precise and keep variation of surface geometry to a minimum.	Technology for manufacturing unit-cells is established. Requires a large number of welds to join unit-cells at the manifold ring segments to form cores. More complicated core-side outlet then A. The fin folding process must be very precise and keep variation of surface geometry to a minimum.	Technology for manufacturing unit-cells is established. Requires a large number of welds to join unit-cells at the manifold ring segments to form cores. More complicated core-side outlet than A. The fin folding process must be very precise and keep variation of surface geometry to a minimum.	Manufacturing 25 mm tubes with external brazed fins is a mature technology. Requires a large number of tube to tube-sheet welds. Clearances among spiral tubes must be tightly controlled to avoid loss of performance.
Cores integration within the pressure vessel	Final assembling and welding of the IHX into the vessel can be complicated.	Final assembling and welding of the IHX into the vessel can be complicated, but simpler than A and C	Final assembling and welding of the IHX into the vessel can be complicated.	Fabrication of a vessel with a diameter > 6 m is a problem. Final assembling and welding of the IHX into the vessel less complicated than A, B and C.
2.2 Transportability				
IHX vessels	Size should not be a problem.	Size should not be a problem.	Size should not be a problem.	Size and weight could be a problem.

Table 1-16 Detailed Comparison of IHX Options A, B, C and Involute (cont'd)

Consideration	Option A Two Rows, Primary Discharge Through Manifold System	Option B Single Row, Double Length Cores Individually Manifolded	Option C Two Rows, Primary Discharge Trough Individual Manifolds	Involute Compact Shell-Tube with External Brazed Fins
2.3 RISK - Manufacturing and Construction				
Individual cores and piping	Individual unit cell low risk. Welding connections and secondary flow seals high risk.	Individual unit cell low risk. Welding connections and secondary flow seals moderate risk with respect A and C.	Individual unit cell low risk. Welding connections and secondary flow seals high risk.	Individual tubes and shrouds low risk. Tube to tube-sheet welding connections and tube bundle assembly high risk.
Cores integration within the pressure vessel	High risk in assembling the IHX and welding its supports.	High risk in assembling the IHX and welding its supports.	High risk in assembling the IHX and welding its supports.	Lower risk in assembling the IHX and welding its supports.
3.0 Operation and Maintenance				
3.1 Reliability and Integrity Management (RIM)				
Individual cores and piping	No planned maintenance required. Reliability affected by the large number of brazed joints/welds, high operating temperatures and potentially high thermal loads.	No planned maintenance required. Smaller PHTS/SHTS pressure boundary (PB) surface in manifolds than A and C. Reliability affected by the large number of brazed joints/welds, high operating temperatures and potentially high thermal loads.	No planned maintenance required. Reliability affected by the large number of brazed joints/welds, high operating temperatures and potentially high thermal loads. Larger PHTS/SHTS PB surface in manifolds than B.	No planned maintenance required. Tube & shell design less affected by high thermal loads than A, B and C. Reliability affected by the large number of tube to tube-sheet welds
Leak detection and isolation	Not practical below IHX level	Might be possible at module level	Might be possible at module level	Not practical below IHX level due to lack of access to outer shroud.

Table 1-16 Detailed Comparison of IHX Options A, B, C and Involute (cont'd)

Consideration	Option A Two Rows, Primary Discharge Through Manifold System	Option B Single Row, Double Length Cores Individually Manifolded	Option C Two Rows, Primary Discharge Trough Individual Manifolds	Involute Compact Shell-Tube with External Brazed Fins
3.2 Performance and Operational				
General	Provides better flow distribution among the unit cell cores than B. New and complicated secondary flow seals design can generate core bypasses.	Possible flow misdistribution among the cores due to longer discharge manifolds and cores. New and complicated secondary flow seals design can generate core bypasses.	Provides better flow distribution among the unit cell cores than B. New and complicated secondary flow seals design can generate core bypasses.	Good flow distribution on the tube-side. Large heat transfer surface required at the shell-side due to poor heat transfer.
3.3 RISK – Operation and Maintenance				
General	High risk. Large PHTS/SHTS PB plate surface operating at high temperature has potential for leaks. Possible bonding of sliding seals on the shell-side may generate shell-side bypasses. Significant leak in PHTS/SHTS PB requires plant shutdown and IHX replacement.	Moderate to high risk. Same plate surface, but less high-temperature manifolds surface in PHTS/SHTS PB than A and C – slightly lower potential for leaks. Fewer, less complex sliding seals on the shell-side with less potential for bonding. Significant leak in PHTS/SHTS PB requires plant shutdown and detection/isolation of leaking module.	High risk. Large PHTS/SHTS PB plate surface operating at high temperature has potential for leaks. Possible bonding of sliding seals on the shell-side will generate shell-side bypasses. Significant leak in PHTS/SHTS PB requires plant shutdown and detection/isolation of leaking module.	Moderate risk. The PB tube surface operating at high temperature has a smaller potential for leaks than A, B and C. No sliding seals on the shell-side with potential for bonding. Large number of tube to tube-sheet welds has potential for leaks. Significant leak in PHTS/SHTS PB requires plant shutdown and IHX replacement.

Table 1-16 Detailed Comparison of IHX Options A, B, C and Involute (cont'd)

Consideration	Option A Two Rows, Primary Discharge Through Manifold System	Option B Single Row, Double Length Cores Individually Manifolded	Option C Two Rows, Primary Discharge Trough Individual Manifolds	Involute Compact Shell-Tube with External Brazed Fins
4.0 Safety and Investment Protection				
4.1 Normal Operation (NO)				
General	No safety concerns. Continuous plant operation is possible in case of small (TBD) leaks between the shell and core-sides	No safety concerns. Continuous plant operation is possible in case of small (TBD) leaks between the shell and core-sides	No safety concerns. Continuous plant operation is possible in case of small (TBD) leaks between the shell and core-sides	No safety concerns. Continuous plant operation is possible in case of small (TBD) leaks between the shell and tube-sides
4.2 Off-Normal Conditions (AOO, DBE)				
General	No safety concerns. Large (TBD) leaks between the shell and core-sides will require replacement of the leaking IHX.	No safety concerns. Large (TBD) leaks between the shell and core-sides will require location/isolation of the leaking IHX module(s).	No safety concerns. Large (TBD) leaks between the shell and core-sides will require location/isolation of the leaking IHX module(s).	No safety concerns. Large (TBD) leaks between the shell and tube-sides will require replacement of the leaking IHX.
4.3 RISK – Safety an Investment Protection				
General	No plant safety risk.	No plant safety risk.	No plant safety risk.	No plant safety risk.
5.0 Lifecycle Cost				
5.1 Design Development Cost (Non-recurring)				
General	The non-recurring design development costs for A, B and C should be approximately the same.	The non-recurring design development costs for A, B and C should be approximately the same.	The non-recurring design development costs for A, B and C should be approximately the same.	The non-recurring design development costs should be higher than A, B and C because application of finned tube-shell technology to IHX-B requires development.

Table 1-16 Detailed Comparison of IHX Options A, B, C and Involute (cont'd)

Consideration	Option A Two Rows, Primary Discharge Through Manifold System	Option B Single Row, Double Length Cores Individually Manifolded	Option C Two Rows, Primary Discharge Trough Individual Manifolds	Involute Compact Shell-Tube with External Brazed Fins
5.2 Capital Cost (Recurring)				
General	The recurring capital costs for A and C should be the same	The recurring capital costs for B should be somewhat lower than A and C, due to the less complex shell-side.	The recurring capital costs for A and C should be the same	The recurring capital costs for the involute design should be higher than A, B and C because application of finned tube-shell technology to IHX-B requires development.
5.3 Project Schedule				
General	The impact on the schedule of the technology development, design and fabrication for the options A, B and C should be the same.	The impact on the schedule of the technology development, design and fabrication for the options A, B and C should be the same.	The impact on the schedule of the technology development, design and fabrication for the options A, B and C should be the same.	The impact on the schedule of the technology development, design and fabrication for the involute should be more severe than A, B and C
5.4 Operating Cost				
General	Since none of the four IHX options requires maintenance, the operating cost should be the same.	Since none of the four IHX options requires maintenance, the operating cost should be the same.	Since none of the four IHX options requires maintenance, the operating cost should be the same.	Since none of the four IHX options requires maintenance, the operating cost should be the same.
5.5 RISK - Lifecycle Cost				
General	Fundamentally covered by risk and cost comments above.	Fundamentally covered by risk and cost comments above.	Fundamentally covered by risk and cost comments above.	Fundamentally covered by risk and cost comments above.

An attempt has been made to summarize and visualize the content of Table 1-16. Four summary ratings have been selected to characterize the content of each individual box in Table 1-17:

- **Good –** For this particular attribute there is a very good chance to meet the requirements for the manufacturing and operation of the IHX within reasonable cost and a minimum of technology development and of safety or investment risk.
- **OK -** For this particular attribute there is a reasonable chance to meet the requirements for the manufacturing and operation of the IHX within reasonable cost and a minimum of technology development and of safety or investment risk.
- **Challenge –** For this particular attribute it is going to be a challenge to meet the requirements for the manufacturing and operation of the IHX within reasonable cost and a minimum of technology development and of safety or investment risk.
- **Not acceptable –** Because of this particular attribute, this option is not acceptable.

Based on the results described in Table 1-16 and Table 1-17, the IHX design indicated as Option C was selected for further evaluation. This design has several advantages with respect the other three design options, A, B and Involute. These advantages include a better coolant flow distribution on the core-side than Option B, primary-return "flex-pipes" from each core discharge header that provides axial and radial compliance not present in Option A, the potential for isolating and plugging a leaking core not available for Option A and an acceptable pressure drop associated with inlet and outlet core piping that is not achievable in Option B. Additionally, the plate-fin unit cell configuration used in Option C does not have the Involutes' shell-and-tube heat exchanger problem of achieving a sufficiently high heat transfer coefficient on the shell-side while keeping a compact configuration.

Table 1-17 Summary of the Detail Comparison of IHX Options A, B, C and Involute

Rating: Good OK Challenge Not acceptable	Option A 	Option B 	Option C 	Involute 
1.0 Design/Technology Development				
1.1 Similarity to DPP SSCs	N/A	N/A	N/A	N/A
1.2 Use of Developed Technologies	OK	OK	OK	Challenge
1.3 RISK - Design/ Technology Development	OK	OK	OK	Challenge
2.0 Manufacturing and Transportability				
2.1 Manufacturability and Constructability	Challenge	Challenge	Challenge	Not Acceptable
2.2 Transportability	Good	Good	Good	Challenge
2.3 RISK - Manufacturing and Construction	Challenge	Challenge	Challenge	Not Acceptable

Table 1-17 Summary of the Detail Comparison of IHX Options A, B, C and Involute (cont'd)

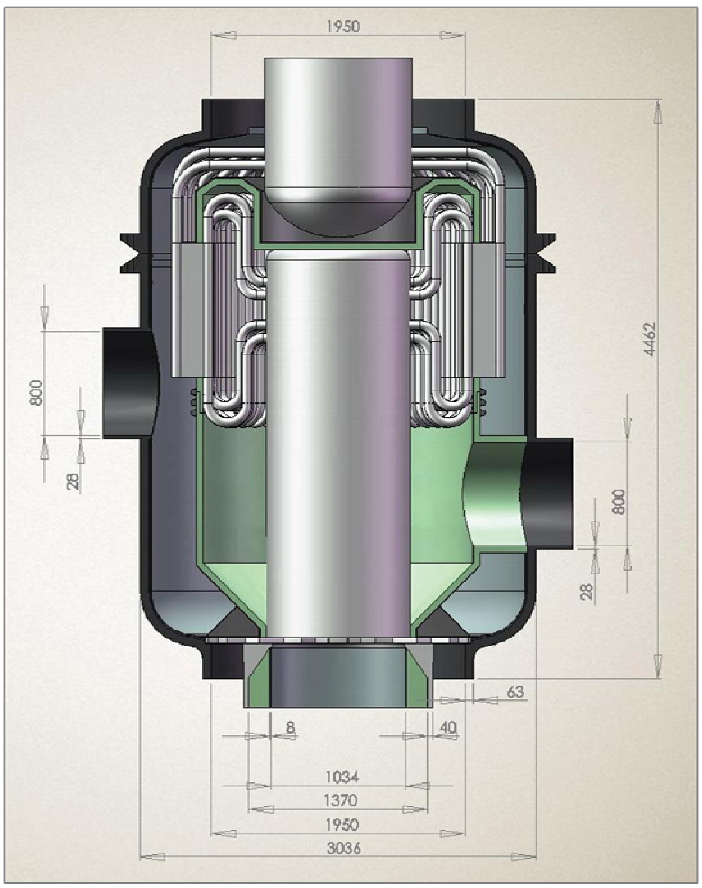
3.0 Operation and Maintenance				
3.1 Reliability and Integrity Management (RIM)	**Challenge**	**OK**	**OK**	**Challenge**
3.2 Performance and Operational	**Good**	**Challenge**	**Good**	**OK**
3.3 RISK – Operation and Maintenance	**Challenge**	**Challenge**	**Challenge**	**Challenge**
4.0 Safety and Investment Protection				
4.1 Normal Operation (NO)	**Good**	**Good**	**Good**	**Good**
4.2 Off-Normal Conditions (AOO, DBE)	**OK**	**OK**	**OK**	**OK**
4.3 RISK - Safety	**OK**	**OK**	**OK**	**OK**
5.0 Lifecycle Cost				
5.1 Design Development Cost (Non-recuring)	**OK**	**OK**	**OK**	**Challenge**
5.2 Capital Cost (Recurring)	**OK**	**OK**	**OK**	**Challenge**
5.3 Project Schedule (FOAK)	**Challenge**	**Challenge**	**Challenge**	**Challenge**
5.4 Operating Cost	**OK**	**OK**	**OK**	**OK**

1.7 Parallel IHX Options

Two unit-cell, plate-fin configurations have been explored using smaller heat exchangers to service two process loops, and a second configuration for a multi-loop array with focus on availability.

1.7.1 Two-Loop Design (Option D)

For a two-loop parallel configuration, Option D, with an IHX-A and B, has the thermal exchange capacity of 255-MWth needed to service each loop (see Section 3.5 for definition of HTS-loop). Shown in Figure 1-46, it bears a strong resemblance to Option B presented in Section 1.4.2.2. In fact, the only difference is the specification of one-meter-tall cores rather than the two-meter cores of Option B, as described in Section 1.4.2.2.



Option D Unit-Cell Integration

- 255 MW_{th} loop service
- Single row of one-meter tall cores
- Cores individually plumbed to headers

Figure 1-46 Option D Cross-Section with Major Dimensions Indicated

1.7.2 Multi-Loop Design (Option E)

An approach to achieving high availability is to employ a parallel array of vessels containing smaller heat exchangers. The essence of this design scheme is to allow failure of one, or possibly more, heat exchangers and still maintain the overall performance at a minimum functional level (based on assumption that failure is not result of common-mode failure). As such, a one-pass approach is assumed over the two-pass series arrangement used for other options discussed in this report. Option E is a notional solution for use in a multi-parallel IHX configuration (see Section 3.5). Presented in Figure 1-47, design choices that simplify construction are allowed by the fewer cores (16) to be packaged per vessel. A total of eighteen vessels are needed to accomplish 510-MW of thermal exchange. With the assumed single-pass heat exchange, the counterflow matrix length is increased to attain the required thermal performance.

Features are indicated in Figure 1-47. With only sixteen cores per vessel, the angular space per core is greater than the prior configurations described, creating a lower packing density. Cores remain oriented in a radial fashion, but are rotated ninety degrees. The counterflow heat exchange direction is therefore parallel to the axis of the vessel. Core inlet manifolds are rigidly plumbed to the inlet header, leaving all strain-relief to the primary-return "flex" pipes between the cores and the primary-discharge header. Figure 1-47 shows a concentric discharge for the heated secondary stream. This is not a preferred feature. However, by increasing the length of the vessel, a plenum can be included to receive the heated gas and direct it through the side of the vessels, as preferred (similar to Option C, see Section 1.4.2).

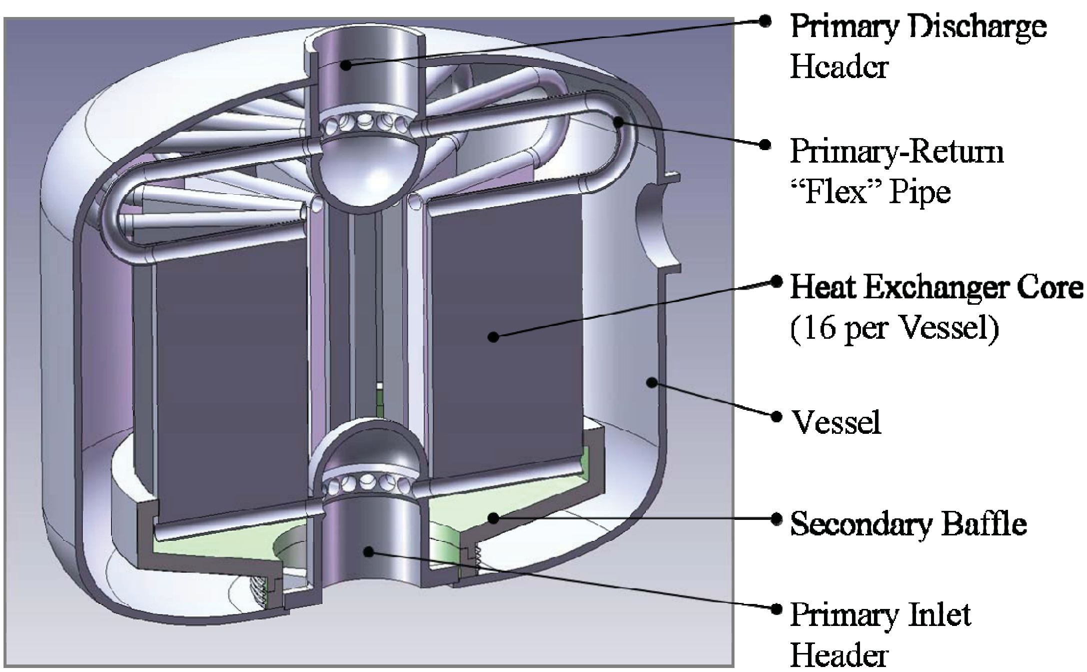


Figure 1-47 Option E, Sectioned, With Features Notes

Flows through this concept are shown in Figure 1-48. As noted above, the principal mechanical difference from Configurations A, B and C is the re-orientation of the cores. Secondary flow is from top to bottom, while the primary flow is from the bottom upward.

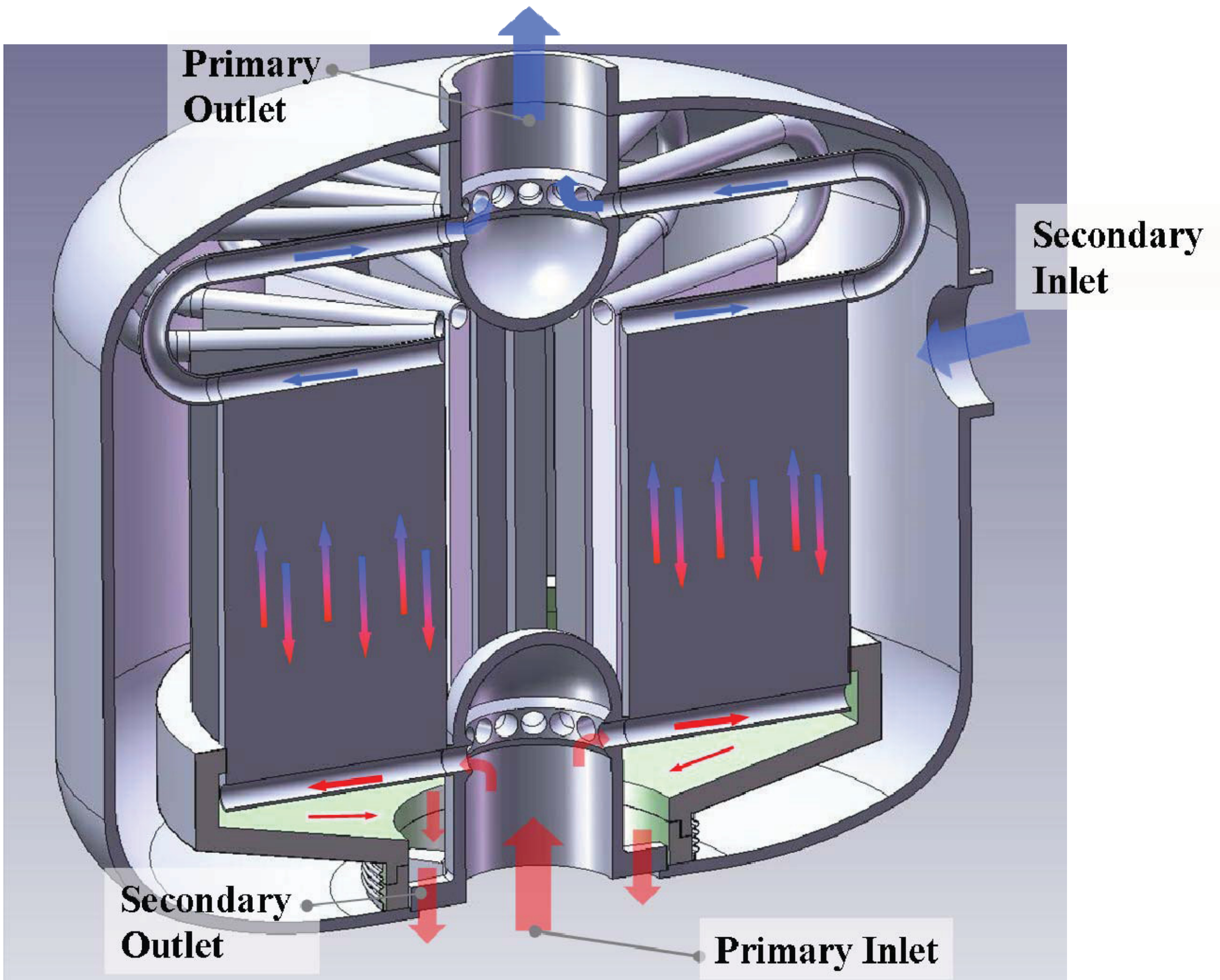


Figure 1-48 Primary and secondary flow circuits through Configuration E

Given that fewer cores are package into each vessel, header diameters are smaller. This and the compactness of plumbing allow a diameter of less than 2-meters. The length as shown in the figures above is 1.9-meters, a dimension that would increase as a side-discharge, consistent with piping design, is included for the secondary.

Being a single-pass design, Option E has the full range of IHX temperatures in each vessel. The durability of all vessels is consequently controlled by the peak operating temperature of 950˚C. In the likely scenario that replacement will be required within the service life of the power plant; all eighteen IHX modules would be replaced on a schedule. The potential advantage, within each replacement interval, is increased availability attendant with eighteen parallel loops (assuming no common-mode failures amongst units and the ability to isolate individual IHXs while continuing to operate the plant). It is noted that his configuration requires more complicated system-level integration, notably the incorporation of an 18-piece reactor outlet pipe/HGD T-junction assembly (see Section 3.5). Due to added complexity, is expected that the potential for increased availability would be offset by reduced reliability.

1.8 IHX Performance

IHX-A and IHX-B are arranged in series, with sufficient heat exchange in IHX-A to deliver primary-side gas to IHX-B at 760˚C, the upper limit for the Alloy 800H assumed for its construction. This prescription, defined in Functions and Requirements in Section 1.2.1 is reduced to the statepoint and performance requirements of Table 1-18.

Table 1-18 IHX State-Points and Specified Performance Parameters for a Two Vessel (Series) Design

	IHX-A		IHX-B	
	Primary	Secondary	Primary	Secondary
Flow, kg/s	159.6	159.7	159.6	159.7
Temp-in, ˚C	950	710	760	287
Press-in, MPa	8.751	9.011	8.683	9.080
Effectiveness, ε	-	0.792	-	0.8943
$\Delta P/P$	0.00617	0.00451	0.0046	0.0062

1.8.1 Unit-Cell IHX Performance

Performance of the unit-cell plate-fin IHX is predicted using a spreadsheet-based model employing the ε-NTU method for thermal effectiveness. Heat transfer and friction data for the wavy-fin surfaces are from Reference 1-4, surface 11.44w. These data are used as a close proxy for data that might be obtained by testing the specific geometries and materials of IHX-A and IHX-B.

The basic construction of the unit-cell is assumed for the thermal hydraulic design. A single internal and two external counterflow matrix fins are given. In addition, the fin-type is exclusively ‘wavy’ and the width across the counterflow is held constant at 50 mm. Variables are principally these:

- Flow Length,
- Fin Height,
- Fin Density (fins per unit-length) and
- Fin Thickness.

These variables are exercised within their practical ranges (functions of manufacturing processes) to achieve the prescribed performance at a minimum relative weight/cost. Table 1-19 provides details for the heat exchanger cores of IHX-A and B. That IHX-B is larger and more massive than IHX-A is a function of the greater performance demanded of it as the cooler, and therefore less technically challenging of the two heat exchangers. That Alloy 617, an alloy perhaps four-times the cost of Alloy 800H, is specified for IHX-A underscores this challenge.

Table 1-19 Design Data for Unit-Cell IHX-A and IHX-B Heat Exchanger Cores

Feature	Dimensions	
	IHX-A	IHX-B
n-Cores	138	170
Matrix		
Flow-length, mm	155	300
Width, mm	50	50
Stack height, mm	1000	1000
n-cells	25270	35230
Internal Fin		
Density, fin/m	1692	1692
Thickness, mm	0.102	0.102
Height, mm	1.905	1.930
External Fin		
Density, fin/mm	1692	1692
Thickness, mm	0.102	0.102
Height, mm	1.30	0.965
Weight, kg	2992	7242
Material	Alloy 617	Alloy 800H

Not surprisingly, predictions shown in Table 1-20 closely match the specified performance parameters.

Table 1-20 Summary of Unit-Cell IHX Performance Predictions

	IHX-A	IHX-B
Thermal Effectiveness, %	79.55	89.62
Primary-Side Pressure Loss, %	0.62	0.46
Secondary-Side Pressure Loss, %	0.44	0.80[3]

Predictive modeling assumes there is no leakage, either secondary-to-primary, or bypass of the secondary side. In practice, there should be no leakage between the two gas streams, but some amount of bypass leakage should be expected on the external pass, assigned to the secondary for this analysis. Figure 1-49 shows the effect of that bypass for rates ranging up to 4% of the prescribed secondary inlet flow to IHX-B.

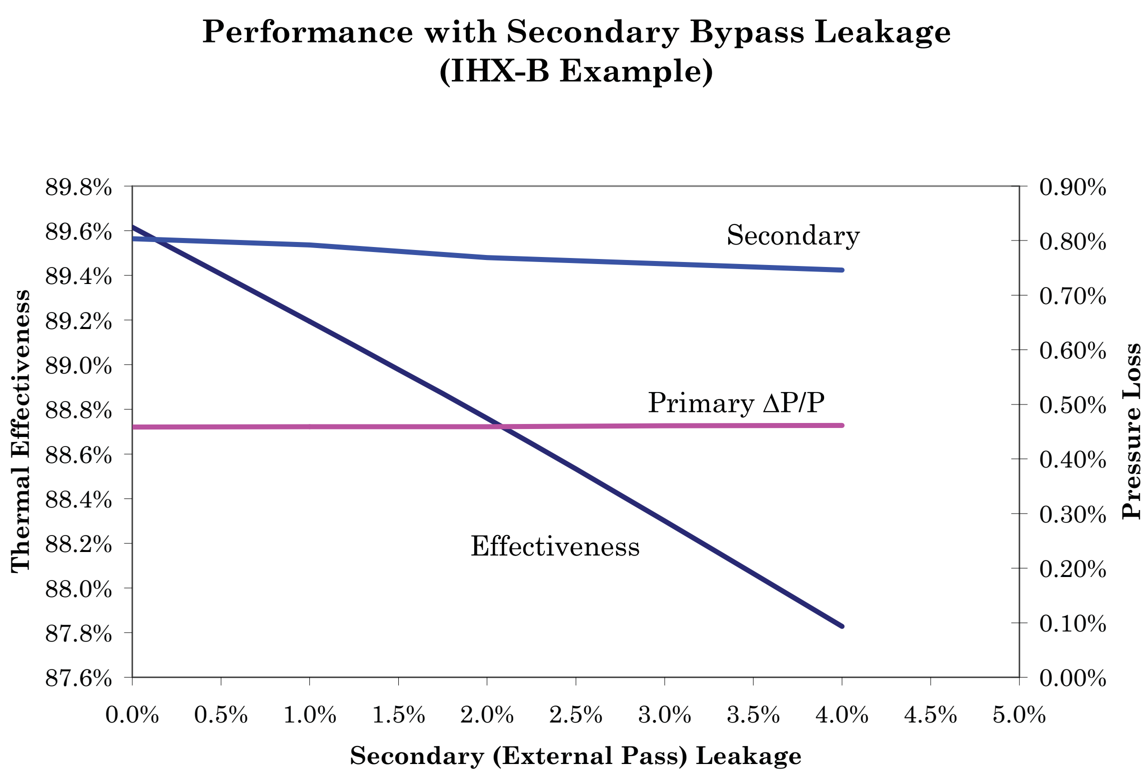


Figure 1-49 Predicted Influence of Secondary Bypass Flow Rate on IHX-B Performance

[3] This value being over the specified 0.620% is due to an error in interpreting the Function and Requirements pressure loss allowance for this pass. Correction to bring this value to within requirements is a small iteration to the thermal hydraulic design and does not affect any conclusions in this report.

Temperature effectiveness, the temperature rise in the secondary pass through the heat exchanger as a fraction of difference between the primary-inlet and the secondary-inlet temperatures, actually rises as its capacity is reduced by the amount of the bypass, i.e. less gas to heat with the constant heating capacity of the primary side. It decreases in an overall sense however when the cooler bypassing streams are mixed back into the main, heated, stream. This mixed-out temperature is presented in Figure 1-49, along with the pressure losses that respond primary to decremented flow on the secondary side.

The influence of secondary bypass, manufacturing process variability, time-dependent leakage and fouling must be considered in establishing performance margins. These are not fully characterized at this point, but will, through testing and analysis, become evident. The thermal-hydraulic design can then be sensibly be amended to account for these performance-degrading effects.

1.8.2 Involute Performance

1.8.2.1 Modeling Approach

Thermo-hydraulic performance of the involute heat exchanger, though strictly crossflow, is most accurately described by counterflow heat-exchange relationships.

Secondary flow, assigned to the inside of the tubes, spirals inward on involute paths as indicated by blue streamlines in Figure 1-50, accepting heat from the primary gas stream. Red tangential streamlines in the same figure indicate the outward flow of the primary gas exchanging heat to the secondary stream. (Values across center are millimeters from the center.) If one were to trace the inward trajectory of a secondary streamline, it would become clear that each successive intersection with a primary streamline is radially closer to the center and therefore hotter. This is the essence of counterflow heat exchange, and the fact that there are many of these progressively hotter intersections is what ultimately compels the counterflow analytic analogy.

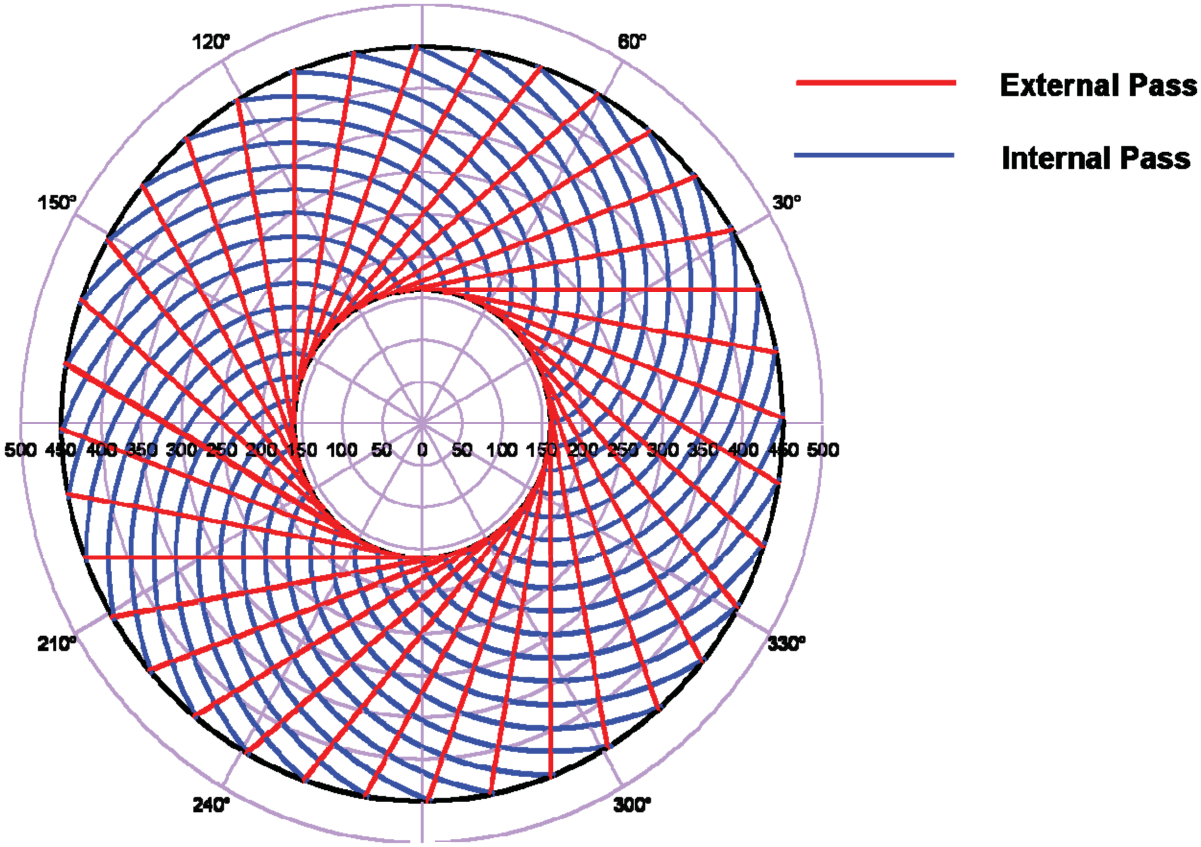


Figure 1-50 Involute Streamlines

An iterative solver was developed to evaluate thermal performance using the ε-NTU method and the Darcy equation for frictional pressure loss. Published data, in the form of the Colburn modulus (St-Pr2/3) and Fanning friction-factors versus the Reynolds Number were used for specific surfaces assigned as proxies to support the calculations. Because the primary fluid flows outward, the cross-sectional area increases, decelerating the gas – an effect accentuated by the increasing density as that stream cools. A numerical approach is therefore taken. The iterative solver developed for this configuration separates the heat exchanger into radial segments. Each segment is treated as a separate heat exchanger that relates thermodynamic statepoints to the adjacent segment – inward in the case of the secondary and outward with respect to the primary stream.

1.8.2.2 Thermo-Hydraulic Design Study

Convective heat transfer rates in laminar tube-flow are inversely proportional to the passage diameter. The heat exchanger designer is therefore inclined to employ smaller diameter tubes, a direction that increases overall surface area as well as promoting greater thermal performance. This tendency is also favorable with respect to durability as hoop stress caused by differential pressure decreases along with thermomechanical stress as a function of lower bending strain.

Commercial processing technology however places practical limits on the diameter of tubes with respect to tube-sheet welding. A search of available equipment places this lower limit at 6 mm. This thermal-hydraulic performance assessment of the involute-tube therefore uses 3 mm as a lower bound for clear-bore tubing, to show the potential with development of specialized welding equipment and processes. To realize a further decrease in hydraulic-diameter, without extending tube welding technology, annular tubes with internal fins, as seen in Figure 1-51, are evaluated as well.

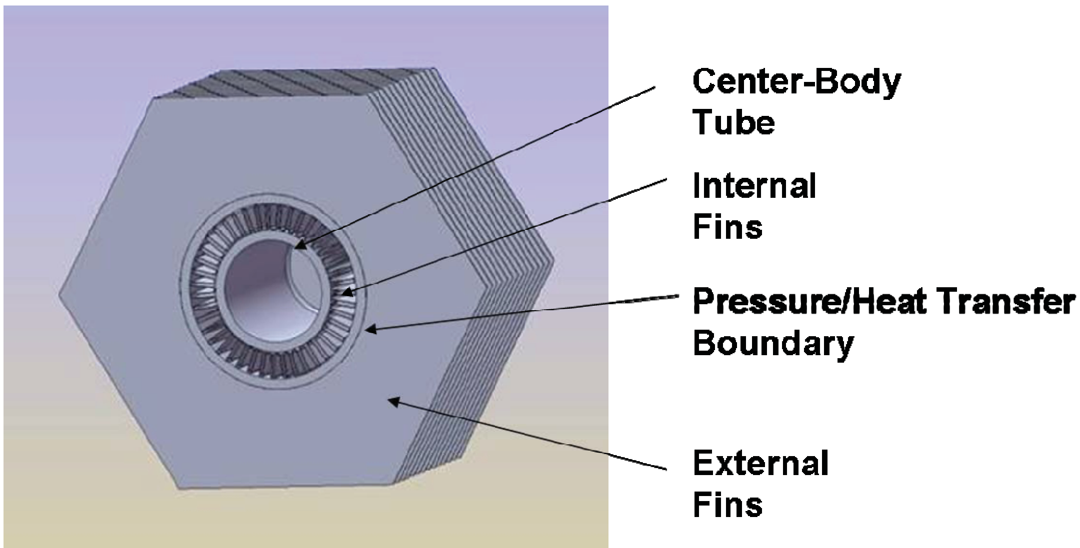


Figure 1-51 Concentric Internally-Finned Annular Tube with Hexagonal External Fins

1.8.2.3 IHX-A Involute-Tube Performance

Smooth-bore and internally-finned tubes with external cross-flow fins were assessed in a constant-performance study, which varied the tube outer diameters. Because the internally-finned variant requires a center-body tube to create an annulus for the folded-fin extended surface, its minimum outer diameter is assumed to be 6 mm. Without this limitation, the smooth-bore tube was analyzed down to 3 mm, suspending the limitation of commercially available welding equipment to make the hermetic tube-header joint. Wall thickness was varied with the diameter of tubes to maintain a constant hoop-stress. This has little influence on performance, but does affect mass. The net matrix height was also adjusted somewhat, in addition to diameter, to achieve identical performance for each tube-diameter analyzed.

The outer diameter of the involute-tube heat-exchange matrix needed to meet the performance requirements of IHX-A as a function of the outer diameter of smooth-bore-externally-finned tube configurations is presented in Figure 1-52. The relationship between tube diameter and heat exchange rate is clearly evident with an increasing matrix diameter needed to meet the requisite performance. There is a small variation in matrix height (1.38 – 1.41-meter) to achieve identical performance for all sizes analyzed.

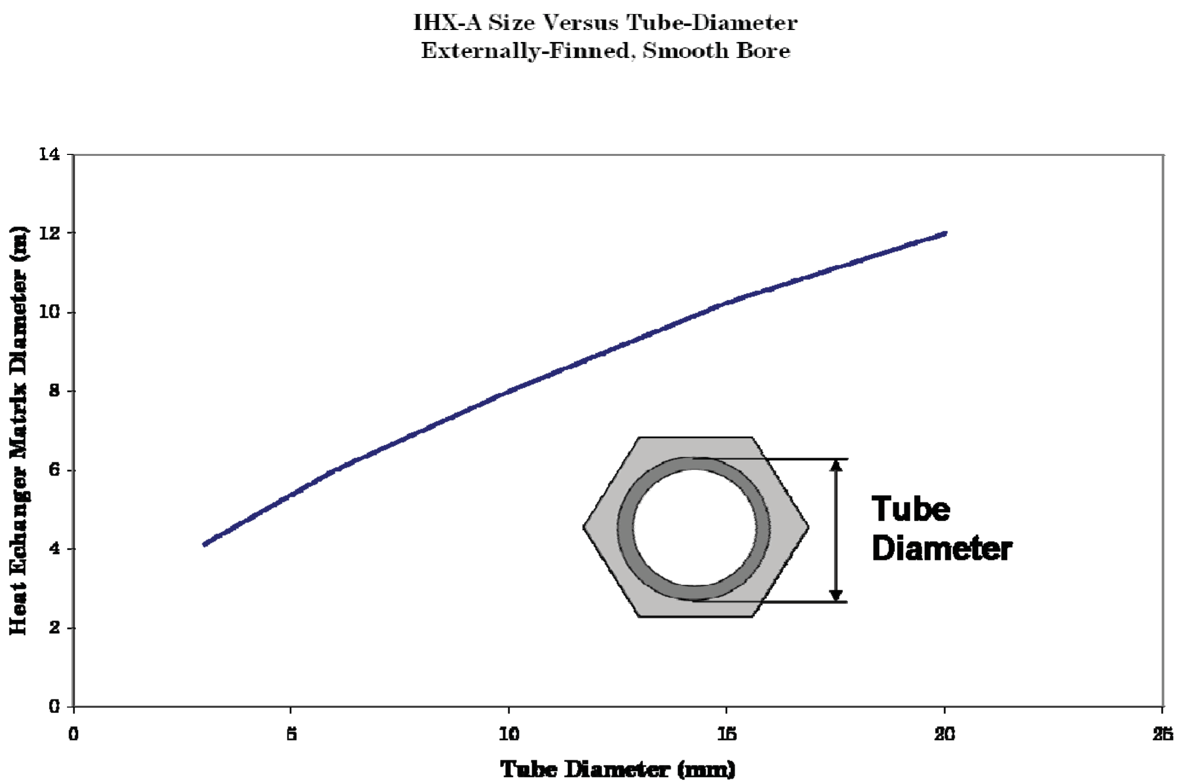


Figure 1-52 Matrix Outer Diameter vs. Smooth-Bore-Involute-Tube Outer Diameter

The internally-finned configuration also increases in overall matrix size similar to its smooth-bore counterpart. The obvious benefit however is that the internal hydraulic diameter is independent of the tube diameter with a constant passage size through the folded fin. The slope of matrix-diameter as a function of tube diameter is therefore flatter for the configurations with both internal and external fins, as seen in Figure 1-53. As before, there is a small variation in matrix height (1.32 – 1.5-meter) generally decreasing in height with greater tube diameter to achieve identical performance for all sizes analyzed.

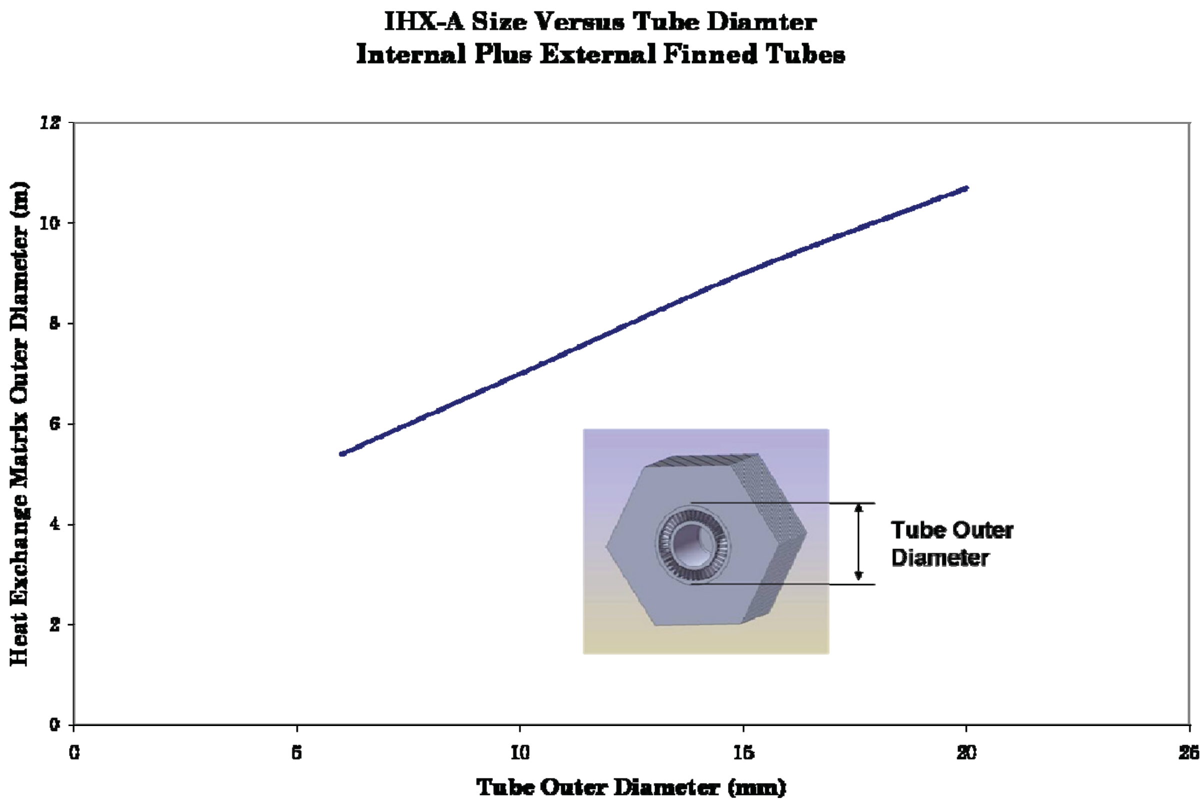


Figure 1-53 Matrix Outer Diameter vs. Internally and Externally-Finned Involute-Tube Outer Diameter

With mass being a fair indicator of cost, Figure 1-54 provides a comparison of the smooth-bore and internally-finned tube configurations. With the external fin-mass the overwhelming fraction of the weight (30-times the tube weight); heat-exchange-matrix weight is driven almost entirely by tube length. The internally-finned tube, being more effective, achieves its heat exchange in a short tube length thus allowing a lighter and more compact configuration.

IHX-B with its greater thermal effectiveness requirement is grossly burdened by the present assumption of flat 0.5 mm-thick external fins. To meet the required performance, a much larger diameter is needed for either configuration tube, as presented in Figure 1-55. Even for a 3 mm tube, smaller than can be welded by commercially available tube-sheet welders, the heat-exchange matrix outer diameter is six meters. Assuming radial margin for the header and outer vessel walls pushes the vessel diameter well beyond the six-meter maximum preferred.

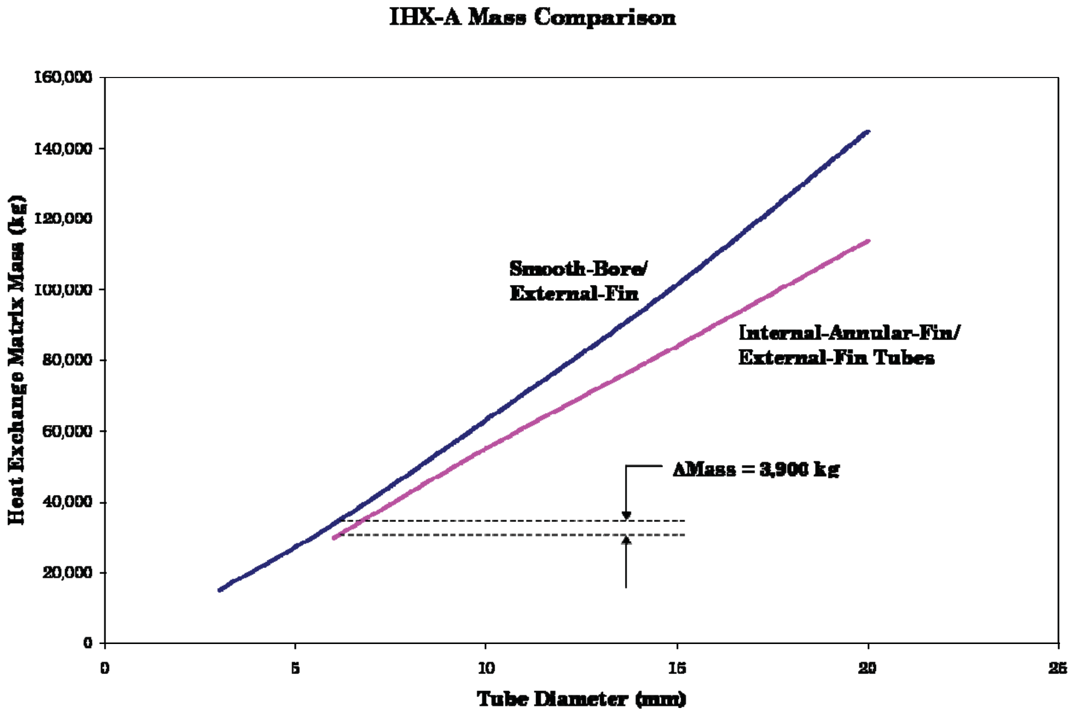


Figure 1-54 Matrix Mass vs. Functions of Involute-Tube Diameter

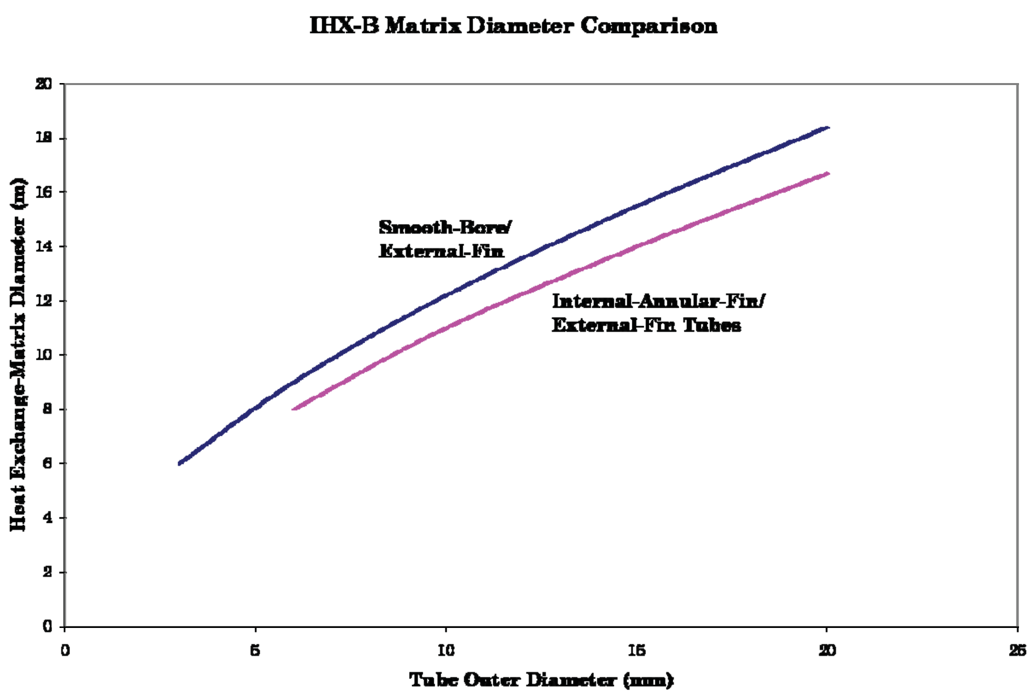


Figure 1-55 Comparison of Heat-Exchange Matrix Diameters for IHX-B

The fact that excess pressure-loss margin exists on the external (primary) pass may be used to enhance convective heat transfer rates and improve compactness. Out of a 1.23% allowable pressure loss on the external side of the heat exchanger for the A plus B passes a small fraction (0.018% ΔP/P) is consumed by the presumed flat fins, as can be seen in Figure 1-56. This represents an opportunity for a surface with a higher frictional loss and with it a higher expected heat transfer rate as well. It may seem curious that internal fins appear to affect external pressure loss. This is a result of less flow area on the external pass because of the shorter tubes needed to meet thermal performance with internal fins.

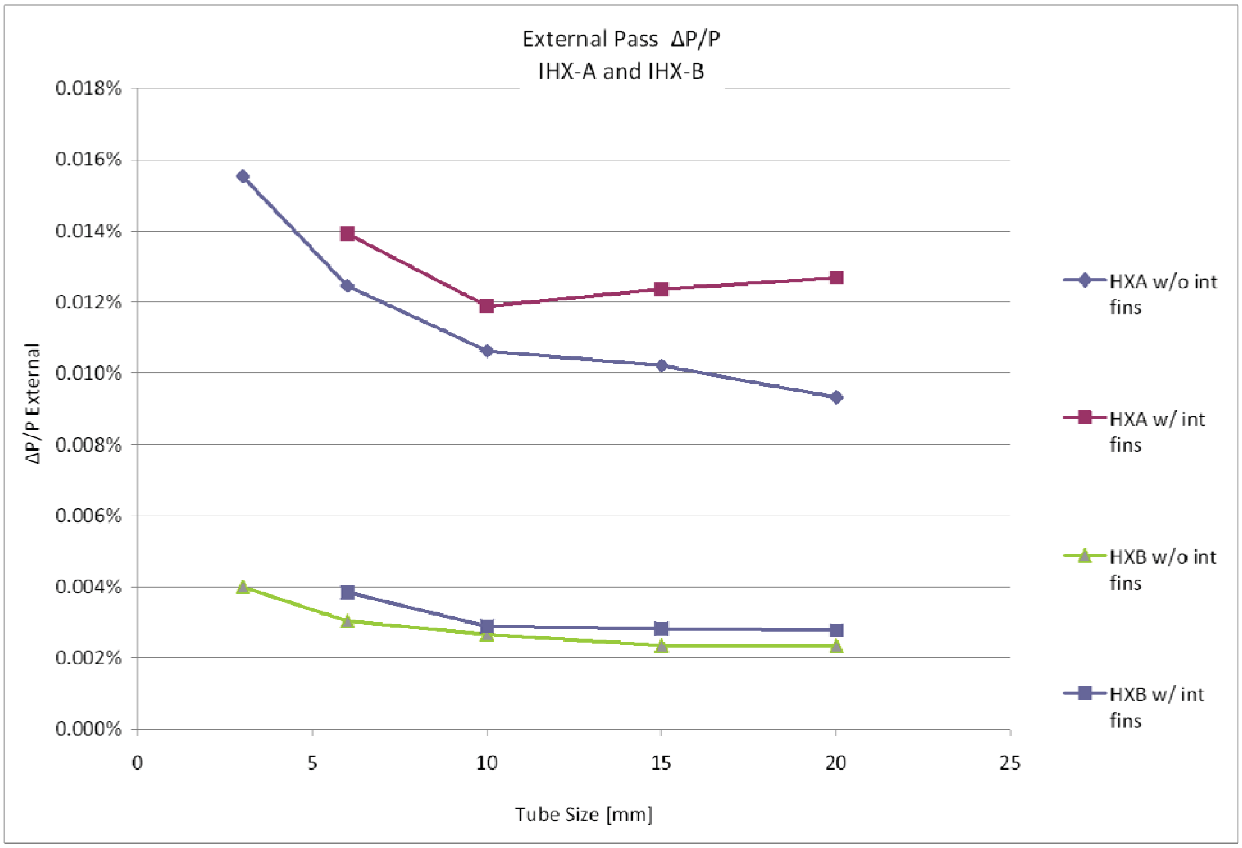


Figure 1-56 External-Side Pressure Losses for Flat-Plate Extended Heat-Transfer Surfaces

Several means of improving the compactness of the heat-exchange matrix were considered. The first is to use smaller tubes (Figure 1-55). This increases the heat transfer rates on both sides of the tubes, obtaining the required heat exchange in a smaller diameter matrix. Development of welding equipment is needed however to realize this improvement. Another means is to space tubes closer, a change that would reduce the height of external fins, increase their efficiency and drive convection coefficients higher. This solution is not practical however because of header strength considerations. As tube spacing decreases headers solidity decreases, compromising strength. Finally, simply increasing the axial length of the heat exchanger core is a much less effective solution because it increases the frontal area on the external and internal passes, lowering the convective heat transfer rate per unit volume of heat exchanger.

While promising as a concept for achieving the needed performance in a simple arrangement, the involute heat exchanger as configured for this design study is impractical for the IHX. The vessel diameter needed to house the IHX-B is in excess of nine meters for 6 mm tubes, a value well in excess of the six-meter maximum preferred to enable over-road transport. Development of an alternative external extended-surface may offer improvements that make the concept viable and perhaps the preferred technology in the future.

1.8.2.4 Metal Foam Extended Surface

The high fractional weight of the external extended surface suggests an opportunity for reductions in size, weight and presumed cost. Present assumptions of external fin thickness and height yield a solidity of 63%. Ni-Cr foams (e.g. see Figure 1-57) have solidity of about 6.7%, hydraulic diameters from 400 – 800 μm and a very high surface-area-to-volume ratio. These attributes could reduce the weight to less than 15% of the values presented in Figure 1-54. Realization, as a minimum, will require development of casting techniques for incorporation with the involute tube, and characterization of heat transfer and friction data for a representative section.

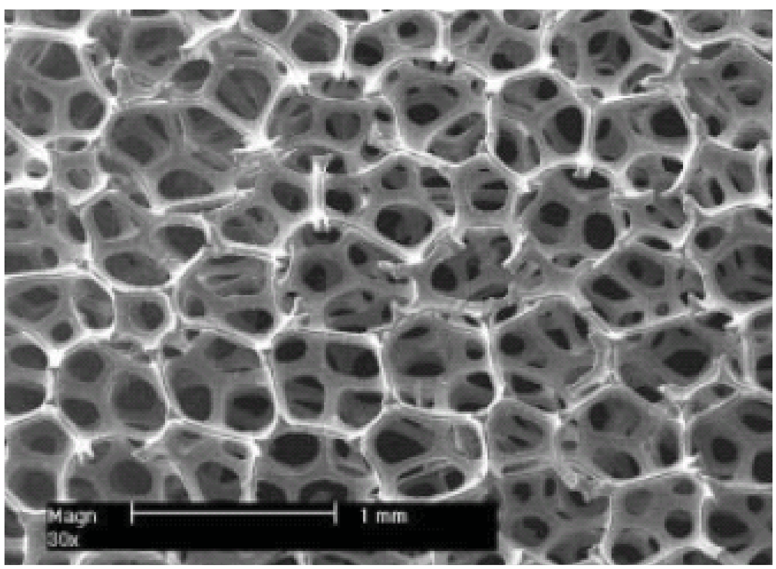


Figure 1-57 INCOFOAM™

1.9 Technology Development

Technical risks have been compiled during the study, and with those risks, options for mitigation. These compilations serve as the basis for inputs to the recommended technology development activities for the unit-cell, plate-fin design.

The unit-cell IHX is based on established nickel-brazed plate-fin heat exchanger technology. New technology is not required for the heat exchanger, per se; however, it is necessary to demonstrate processing techniques and to understand the survivability of the resulting structure as applied to the NGNP. Specific technical risks to be addressed are tabulated in Table 1-21. These and the mitigation options cited form the basis for the following plan-steps for technology development needed to determine suitability to the NGNP IHX.

1.9.1 Brazed Plate-Fin Unit-Cell Technology Tasks

The following items address Items 1-3 in Table 1-21:

A. Prepare brazed plate-fin coupons using methods intended for unit cells. This step will exercise braze filler metal forms (e.g. powders, foils) and furnace cycle parameters to produce acceptable results as determined by hydrostatic burst testing and preliminary micrographic evaluation.
B. Evaluate groups of samples prepared per the selected materials and processing parameters. This evaluation includes micrographic examination, micro-chemical analysis and room-temperature hydrostatic burst testing.
C. Based on affirmative results from step-B, procure the minimum tooling needed to produce representative unit cells.
D. Qualify processes to produce unit-cells based on parameters established for coupons in step-A.
E. Submit cells to hydrostatic burst testing and micrographic evaluation.
F. Conduct hydrostatic creep-rupture tests at 950˚C and +9-MPa and -9MPa to characterize:
   a. Time to failure under externally pressurized and internally-pressurized loss-of-secondary pressure events
   b. Failure mode-shapes associated with expanding and collapsing hydrostatic pressurization. This determines whether structural failure includes a breech of the pressure boundary of the heat exchanger core.
G. Conduct long-term exposure tests of selected material combinations for IHX-A and IHX-B at various elevated temperatures in a representative atmosphere. Evaluate samples periodically for microstructural changes and changes in mechanical properties.

Table 1-21 Unit-Cell IHX Technical Risks and Mitigation Options

Technical Risks	Mitigation Options
1. Mechanical properties of braze joints at 950˚C may be inadequate for high-load loss-of-secondary event.	a) Characterize mechanical properties of braze joints at temperatures up to the peak operating temperature. b) Perform metallographic analysis and micro-chemical analyses of brazed structures to provide basis for predicting behavior c) Test sample cells, cores or sub-core assemblies at simulated event conditions.
2. Mechanical properties of brazed assembly may not be constant with exposure to operating environment. This may degrade (or enhance[4]) strength or ductility with operation.	a) Expose brazed samples to operating environment, including: temperature, atmospheric composition, pressure and stress. b) Observe changes to micro-structure, mechanical properties and creep characteristics with exposure
3. Diffusion of braze alloy into parent metals can have degrading (or enhancing[5]) effect on corrosion resistance.	a) Mitigation activities for item-2, above.
4. Self-welding of unit-cells at slip-plane may inhibit low-stress deflection during start-stop maneuvers.	a) Conduct tests to evaluate self-welding of fins at respective operating temperature ranges and ranges of atmospheric chemistry for candidate alloys. b) Research coatings to mitigate self-welding c) Test coatings to validate efficacy.

1.9.2 Self-Welding Technology Task

The following items address Item 4 in Table 1-21:

A. Review available data for self-welding of candidate materials in representative atmospheres and temperatures.
B. Review coating and processing technologies available for mitigation of self-welding potential.
C. Where gaps in data exist per Step-A, expose sample fin materials, bare and with weld mitigating processing, to exposure and representative mechanical pressures (dead weight) for periods up to one-year.
D. Evaluate all samples including shearing force required for release.

[4] At 950˚C additional diffusion of residual intermetallic islands in braze fillets will tend to strengthen braze joints.
[5] The higher concentration of nickel in braze filler metals may enrich the parent metal via diffusion, making it more corrosion resistant.

1.10 References

1-1 *NGNP and Hydrogen Production Preconceptual Design Report*, NGNP-01-RPT-001, Special Study 20.3 – High Temperature Process Heat Transfer and Transport, January 2007.

1-2 Peterson, P.F., Capillary Tube and Shell Heat Exchanger Design for Helium to Liquid Salt Heat Transfer, Report UCBTH-07-003, University of CA, Berkeley, CA, May 7, 2007.

1-3 *NGNP and Hydrogen Production Preconceptual Design Report*, NGNP-ESR-RPT-001, Revision 1, Westinghouse Electric Company LLC, June 2007.

1-4 Kayes, W.M. and London, A.L., *Compact Heat Exchangers (Third Edition)*, Krieger Publishing Company, 1984.

2 IHX MATERIALS

This section addresses material alternatives for the IHX. In Section 2.1, the initial materials survey, which was completed as part of the PBMR NGNP Preconceptual Design, is updated. Considerations related to fabrication are also evaluated in Section 2.1. Section 2.2 addresses material lifetime issues, including creep, fatigue and corrosion. Section 2.3 provides a summary of new and revised technology development requirements for IHX materials that result from the present study.

2.1 Materials Survey

2.1.1 Previous IHX Materials Reviews and Recommendations

An assessment of the readiness of the IHX for the NGNP was undertaken as part of Special Study 20.3 (Ref. 1-1). It was recognized in Ref. 1-1 that the "technical barriers associated with the IHX…have the potential to drive the NGNP schedule and significantly influence decisions regarding the overall configuration of the HTS". Therefore, supporting assessments were conducted to evaluate IHX designs, identify and evaluate potential materials for the IHX, and to determine the status of applicable codes and standards. Further, where technology shortcomings were identified, Design Data Needs (DDNs) were prepared as input to the NGNP Preconceptual Design (Ref. 0). These DDNs have been updated as part of the present study (See Sections 2.3 and 4).

Some of the key assumptions and parameters applied in the assessments of IHX designs and materials included the following:

- The nominal reactor outlet temperature to the PHTS is 950°C.
- The nominal temperature at the exit from the IHX to the SHTS is 900°C.
- The pressure in the primary loop (PHTS) is to be nominally 9 MPa and is essentially pressure balanced with the secondary loop (SHTS).
- The design life for any replaceable components will be >10 years with a target of 20 years.

Shell-and-tube and plate-fin, prime surface, and PCHE compact designs were examined and evaluated for the IHX and these comparisons have been updated in the present study (Section 1.1). The shell-and-tube design was eliminated as a candidate for the IHX, as it was judged not to be commercially viable because of lack of compactness and high cost. The PCHE was selected from among the compact designs as the initial Preconceptual Design reference for the NGNP IHX because it was perceived to be the most robust and had a solid basis of commercial experience, albeit at lower temperatures. The current study, however, is also looking at design features specific to plate-fin compact heat exchangers, based on their efficient materials usage and excellent transient response characteristics. Materials aspects related to the design and fabrication of plate-fin heat exchangers are addressed herein.

A large number of Fe-, Fe/Ni-, and Ni-base alloys were earlier examined in the NGNP program as potential candidates for the IHX. Special Study 20.3 selected some of the most promising of these and evaluated them in detail. These included Haynes 556 (Fe-Ni-Cr-Co), Alloy 230 (Ni-Cr-W), Hastelloy X and Hastelloy XR (Ni-Cr-Fe-Mo), Alloy 617 (Ni-Cr-Co-Mo), Haynes HR-120 (Fe-Ni-Cr), Haynes RA-330 (Fe-Ni-Cr), and Alloy 800H and Alloy 800HT (Fe-Ni-Cr). Of these, the greatest service experience exists for Alloy 617, Alloy 800H, Hastelloy X and Hastelloy XR. The Hastelloy XR variant was judged to be the most resistant to corrosion in impure helium, but its strength is inferior when compared to Alloy 617 and Alloy 230. It was noted that Hastelloy XR would be a very viable candidate for an IHX design with relatively low design stresses or a lower temperature requirement. Finally, only Alloy 800H is approved for nuclear service under ASME Section III, Subsection NH and then only for design temperatures up to 760°C. All of the other alloys are covered in ASME Section VIII.

The Special Study concluded that, all things considered, Alloy 617 and Alloy 230 are the best available alloys for the 900-950°C IHX applications. Other studies have made similar recommendations. For example, Alloy 617 and Alloy 230 were the IHX materials choices from INL NGNP work (Ref. 2-3). A study at ANL also critically evaluated Alloy 230, Hastelloy X, Alloy 800H, and Alloy 617 for IHX application and recommended the latter (Ref. 2-4).

The Special Study also concluded that 850°C was qualitatively the likely highest temperature that could be supported in a 60-year IHX and that sections of the IHX operating at higher temperatures would need to be designed for replacement. Based on this, a high temperature IHX-A and a lower temperature IHX-B operating in series was proposed. Alloy 800H was tentatively selected for the IHX-B material with a temperature limited to 760°C, the maximum temperature for which Alloy 800H has obtained ASME Section III approval.

Technology gaps or areas of technology uncertainty associated with the use of Alloy 617 and Alloy 230 were identified and discussed in References 2-5 and 2-6. These resulted in the proposal for DDNs covering material specifications and material acquisition, thermal/physical and mechanical properties, welding and as-welded properties, aging and environmental effects, and influence of grain size on properties. Both Alloy 617 and Alloy 230 were covered in these DDNs. Also included in the DDNs were structural mechanics tasks related to high-temperature stress-strain modeling methods and to criteria for acceptable levels of stress-strain. Finally, there was a DDN aimed at supporting ASME Section III code cases for Alloy 617 and Alloy 230. Typically, the DDNs were required for completion in 2012.

2.1.2 Materials R&D Efforts in 2006 and 2007

Progress on IHX materials R&D in the US was severely constrained in both 2006 and 2007 by budget limitations and uncertainties. There appear to be reasonable expectations that acceleration of the programs can begin in 2008. More specifically, the status of progress during the above-mentioned period is captured in the following:

- The desired fine-grained heats of Alloy 617 and Alloy 230 have not been procured.

- Efforts were initiated and are ongoing on fatigue testing of Alloy 617 in simulated NGNP PHTS helium.
- Weld specimens of Alloy 617 were prepared and are currently being tested.
- Significant levels of effort were initiated relative to the aging and environmental testing of alloys.
- Nothing has yet been done on the effects of grain size on properties.
- Some progress has been made on simplified methods and constitutive equations for high-temperature design.
- A Joint ASME/DOE study has provided the data base and basis that could permit ASME Section III incorporation of Alloy 800H at temperatures up to 900°C, if desired.

A French effort directed toward Alloy 617 and Alloy 230 has continued as part of the Gen IV GIF VHTR development program. Work ongoing and planned on these alloys was described in a paper, (Ref. 2-7) presented in Paris in September 2005. Work proposed for 2006 and beyond included mechanical properties, thermal stability, and corrosion resistance as well as work on diffusion bonding. Relative to thermal stability, it was found that ductility losses as a result of thermal aging were at a maximum after aging in the range 700-750°C. The residual levels of ductility, subsequent to aging, can still be considered adequate for structural applications. This would be of no concern for materials in IHX-A operating at much higher temperature. There was no effect of aging on strengths at temperatures >800°C. The corrosion work is ongoing in a Helium atmosphere with the following impurity levels 200 vpm H_2, 50 vpm CO, 20 vpm CH_4, 2 vpm H_2O. Study was also being made of the applicability of Fe- and Ni-base ODS alloys for high temperature use in VHTRs.

2.1.3 Fabrication-Related Metallurgical Factors

Fabrication of compact heat exchange cores for an IHX involves several metallurgical factors that are specific to these designs. First, both the plate-fin and PCHE compact designs require the use of very thin sections of material. On this basis, the specification of grain sizes much smaller than those previously used in applications of the high temperature materials involved has been suggested. The implications of thin sections and small grain sizes on materials properties and behavior are discussed below in Section 2.1.3.1.

Also, the assembly of plate-fin heat exchange cores will require brazing, using Ni-base braze alloy. Fabrication of PCHE heat exchange cores will be accomplished by using the solid-state diffusion bonding technique. The development of brazing and diffusion bonding processes and the effect of these processes on the properties and behavior of the resultant joints will be discussed below in Section 2.1.3.2.

2.1.3.1 Thin Section and Grain Size Effects

The heat exchange cores of both the plate-fin and PCHE IHX designs are fabricated of thin sections of material. This, of course, minimizes total mass and thermal stresses and improves efficiency. The design of the plate-fin heat exchange core currently being evaluated has fins of 0.102 mm (0.004 in.) thickness and plates of 0.38 mm (0.015 in.) thickness. (Note that, according to the ASM, sheet materials with thickness <0.006 in. are classified as foils.) Although dimensions specific to an equivalent PCHE design are not currently available for direct comparison, PCHE assemblies typically employ plate materials >0.5 mm (>0.02 in.). In some cases, however, the plates may be as thin as 0.2 mm (0.008 in.). The flow channels are etched or pressed into the PCHE plates, resulting in an effective thickness less than the original plate thickness.

Several questions come to mind relative to the possible effects of employing such thin materials in the heat exchange cores. First, will ease and/or effectiveness of joining, either by brazing or diffusion bonding, be affected by these thin sections? There appears to be no reasonable hypothesis by which diffusion bonding should be influenced by thickness and, as to brazing, materials of such thickness are routinely brazed in commercial practice. The second question, then, involves any possible effects of section thickness on properties such as creep strength, fatigue resistance, and ductility. There is little or no information readily available on this subject, but the fabrication procedures necessary to achieve various thicknesses and product forms could result in differences in structures (e.g., dislocation densities and forms) that might influence properties. The effects should not be expected to be large but this requires testing and verification. Finally, corrosion (i.e., reactions with impurity species in the helium coolant resulting in surface and internal oxidation and carburization or decarburization) will likely occur to some level. Will this be of such degree that it can degrade the integrity and long-term performance of the heat exchanger cores? The degree of attack will be dependant on the materials involved, the chemistry of the coolant, temperature, time at temperature and protectiveness and integrity of any oxides formed. To evaluate the degree of corrosion we need reaction rate data relative to all of the parameters above. Finally, the effects of this corrosion on properties and material behavior need to be determined, especially in the product configuration that the material is to be utilized.

In our previous study relative to NGNP and Hydrogen Production Preconceptual Design, it was recommended that the materials used in compact heat exchange cores have grain sizes in the range ASTM 6-8 as opposed to ASTM 0-3 normally seen in commercial products of high-temperature alloys such as Alloy 617 and Alloy 230. The number of grains as a function of ASTM grain size is shown in Table 2-1. As can be seen, the higher the ASTM Grain Size, the smaller the size of the grains. The selection of use of these high-temperature alloys with grain size range commonly ASTM 0-3 is based on the optimization of creep strength under the experience-based expectation that larger grains impart greater creep resistance. This improvement in creep resistance, however, is purchased at the expense of fatigue strength and reduced tensile properties at given temperature. The goal of the recommended grain size of ASTM 6-8 was to gain increased fatigue resistance and to avoid through-section leakage paths associated with small flaws in the grain boundary structure. The typical grain size number specification for Alloy 800H is equal or less than ASTM 5.

Table 2-1 Numbers of Grains versus ASTM Grain Size Number

ASTM Grain Size Number	Number of Grains per mm^2
0	8
1	16
2	31
3	62
4	124
5	248
6	496
7	992
8	1980

Given the above, the questions listed below are important and worthy of investigation.

- What is the effect of grain size on creep, fatigue, and tensile properties?
- What grain size is required to ensure the fatigue integrity of the plate and fin materials in the plate-fin heat exchange core and of the plates in the PCHE?
- Will grain size numbers greater than ASTM 6 reduce creep strength to the extent that thicker sections might be required in the heat exchange cores?
- Will grain size have any effect on corrosion mechanisms or rates?

With regard to fatigue, as noted in the first question above, the Special Metals on line (www.specialmetals.com) descriptive material for Alloy 617 gives the following information for grain size effects. Specimens of Alloy 617 with grain size numbers of ASTM 2.5, 5.0, and 9.5 were tested under a tension-tension axial stress in a fatigue cycle with stress varied between 35 MPa to 414 MPa. The resulting number of cycles to failure was 500 for the ASTM 2.5 grain size material, 6.4 x 10^3 for that with the ASTM 5.0 grain size, and 9.3 x 10^3 for that with ASTM 9.5. It is obvious from this result that the fatigue life is increased very significantly in going from ASTM 2.5 (44 grains/mm^2) to ASTM 5.0 (248 grains/mm^2) and to a lesser extent in going from ASTM 5.0 to ASTM 9.5 (5610 grains/mm^2). Finally, with respect to the last question posed above, there is evidence from studies on the corrosion of Ni-base alloys that oxide morphology, chemistry, and thickness can be affected by grain size with the finest grain size producing the most desirable result (see Ref. 2-7).

2.1.3.2 Joining Technology

Brazing will be used to assemble the heat exchange cores of the plate-fin IHX. Brazing, in general, is the joining of two base materials with a filler metal (braze alloy) that has a melting point lower than those of the base materials. In our case the braze alloy will be Ni-base with Cr levels in the range 7-22% and elements such as Si and P added to lower the braze alloy melting point. Cleanliness of all surfaces to be joined is a critical element to achieve successful and repeatable brazed joints. Proper fixturing using materials with good stability at the brazing temperature is also very important as is providing the proper brazing environment (dry H_2, inert gases, or vacuum). Use of a vacuum atmosphere is particularly important when the materials to be brazed contain significant levels of Al+Ti. In theory, the Al and Ti oxides will, under vacuum, evaporate from the surfaces of the materials to be brazed and provide a clean surface for the wetting and flow of the filler metal. In practice, however, a flash coating of Ni (0.004-0.006 in.) is applied to the base metals to facilitate wetting and flow. (Note that the specification for Alloy 617 permits Al+Ti over the range 0.8-2.1 %.) The cleaned and fixtured assembly is heated to a temperature just below that required for melting of the braze alloy and allowed to equilibrate. It is then heated quickly to the brazing temperature and held at that temperature for a period of time sufficient to permit diffusion but not to allow excessive grain growth. The brazing process results in a composite metal structure with properties that may be different from those of the base and filler metals. However, perhaps counter to intuition, the temperature-related properties of the resulting brazed joint do not necessarily constitute a weak link within the resulting structure. References 2-8, 2-9 and 2-10 provide some information on the properties of such joints produced using Ni-base braze materials. The *ASM Handbook* (Ref. 2-8) shows that the tensile and short-term (100 hour) creep-rupture properties of a Co-Cr-W-Ni alloy (Haynes 25) braze joint are essentially identical to those for the base metal over the temperature range 816-982°C. The *Welding Journal* (Ref. 2-9) compares the ultimate tensile strengths of AMS 5770 (Fe-Cr-Ni-Co) base metal and braze joints over the range 427-1093°C and finds that they are equivalent. The *Welding Research Supplement* (Ref. 2-10) examined stainless steel (316L) braze joints and concluded that their tensile and fatigue properties were as good as those of the base metals.

There are still uncertainties relative to the brazing of Alloy 617, Alloy 230, and Alloy 800H. For example, which braze alloy or alloys should be used for assembly of the plate-fin heat exchange cores? What processing conditions should be employed? What are the resultant characteristics of the braze joints? Relative to the latter, braze joint integrity needs to be addressed by testing of trial plate-fin brazements. Assessments also need to be performed of the transport of braze filler metal elements into the base metal (and the reverse) and into the coolant stream during operation. Characterization of the braze/base metal composite structure by metallography, chemistry, and properties is also desirable. Finally, what effects might aging and/or environmental exposure have on the properties of the braze joints?

Diffusion bonding is the joining method that will be used for the assembly of IHX heat exchange cores employing the PCHE design. In its simplest form, diffusion bonding is a process by which two nominally flat, clean interfaces can be joined at an elevated temperature (typically about 50-80% of the absolute melting temperature of the parent material) in a vacuum or inert atmosphere using an applied pressure for times ranging from a few minutes to a few hours. The loads used are usually below those that would cause macro deformation of the parent materials. The process has the ability to produce high quality joints so that neither metallurgical discontinuities nor porosity exist across the interface. With properly controlled process variables, the diffusion-bonded joint should have strength and ductility equivalent to those of the base metals.

There is significant commercial experience with the diffusion bonding of stainless steels and Ni-base alloys, including Alloy 617. Even so, there are questions that need to be answered relative to diffusion bonding of the PCHE heat exchange cores. These include the following.

- What are the appropriate diffusion bonding temperatures for our alloys?
- What loading levels and environments are required?
- What holding times are needed at the diffusion bonding temperature?
- What is the strength of the diffusion bond?
- How can the resultant microstructure be controlled and optimized?

Relative to this latter point, we expect that a properly prepared and processed diffusion bond should have the same properties as those of the materials joined. Can the diffusion bonding process have affected long-term properties, aging behavior, or environmental response? This is unlikely, but still worthy of further consideration.

2.1.3.3 Manufacture of Plate-Fin Heat Exchange Cores

This section is directed specifically to the manufacture of unit-cells of a plate-fin heat exchanger. (However, some of the items addressed would also apply to the manufacture of PCHE units.) Overall, plate-fin unit cell manufacture involves die-forming, blanking (die or line-cutting, e.g. laser), fin-folding, resistance welding, nickel brazing, and welding.

To create a unit-cell IHX, parting sheets and fins must be formed by mechanical working. Fins are tightly folded and formed in waves to promote heat transfer, while sheets are stamped to produce an elevated land around the periphery for the braze joint. All materials under consideration for the IHX are commonly formed into various shapes (e.g., combustors and bellows). A qualitative indication of the formability or plasticity of a material is the ratio of its tensile strength to its yield strength. As seen in Table 2-2, the formability of each of the IHX candidate alloys is good, and the formability of Alloy 800H is exceptional.

Parting sheets, fins and rings are brazed to create a unit cell, the "building-block" of the unit-cell plate-fin IHX. This is a furnace operation conducted in a controlled atmosphere or vacuum using a nickel-based eutectic filler metal to bond the constituent details. A variety of alloys are available in forms ranging from powder to amorphous foil, and in a wide range of compositions. A specific alloy is not recommended here, as several would be tested in the course of process development and qualification. The correct alloy and process parameters can produce braze joints approaching the strength of the parent metals.

Table 2-2 Formability of IHX Candidate Alloys as Indicated by Their Tensile Strength to Yield Strength Ratios

IHX Candidate Material	Ratio of Tensile to Yield Strength
Alloy 800H	3.5
Alloy 617	1.8
Alloy 230	2.0

The strength of the resulting composite brazed plate-fin structure can be affected by the composition of the base alloy. As was noted in Section 2.1.3.2, oxides of elements such as aluminum and titanium can inhibit wetting of molten braze filler metal (required to form strong fillets). Alloy 800H and Alloy 617 both employ these elements (levels of Al + Ti of 0.3-1.2% and 0.8-2.1%, respectively) and this could present a challenge to proper wetting. Given good vacuum levels or a pure reducing atmosphere, these oxides should be stripped/evaporated from the surface during the braze cycle. If, during process development, adequate wetting is not observed or is inconsistent, nickel coatings may be applied to the base metal to present an oxide-free bond surface for brazing. Haynes 230 has a relatively low concentration of aluminum, suggesting good wetting potential.

The unit cells of the IHX will be joined manifold-to-manifold by autogenous orbital welds. These welds will, ideally, be non-structural, with hydraulic loads carried by continuous, non-welded structures. All candidate materials are readily welded.

2.1.4 IHX Materials Data and R&D Status

Technology gaps and uncertainties relative to the use of Alloy 617 and Alloy 230 were identified in References 2-5 and 2-6 and discussed in Section 2.1.1 in terms of DDNs. Further, Section 2.1.2 described the status and progress being made in addressing these technology needs. Table 2-3, presented below, is intended as a summary status of materials technology needs for Alloy 617 and Alloy 230, the materials first recommended for compact IHXs, and for the Alloy 800H material tentatively selected for IHX-B.

Note that for the materials Alloy 617 and Alloy 230 there is additional data/information/ action required in all of the materials technology areas listed in the table. The technology status for Alloy 800H is more advanced than for the other two alloys. However, information and data are still needed relative to thin section and grain size effects and to joining technology, both brazing and diffusion bonding. The data needed dates are those proposed in 2006 and 2007. No later information is currently available.

Table 2-3 Summary of Technology Area Needs and Status for IHX Materials

Materials Technology Area	Additional Data Needed for Alloy 617	Additional Data Needed for Alloy 230	Additional Data Needed for Alloy 800H	Date That Data Is Needed
Base Material Properties	Yes	Yes	No	2012
As-Welded Properties	Yes	Yes	No	2012
Aging and Environmental Effects	Yes	Yes	No	2012
Grain Size and Section Thickness Effects	Yes	Yes	Yes	2012
Brazing and Diffusion Bonding Technology	Yes	Yes	Yes	2010
High Temperature Design Methods	Yes	Yes	No	2010
ASME Code Case Activities	Yes	Yes	No*	2012

*Not as long as the temperature of Alloy 800H in IHX-B is limited to 760°C.

2.1.5 Selection of IHX-A and IHX-B Materials

After reviewing our previous recommendations as to materials for the heat exchange core of compact IHXs (i.e., Alloy 617 or Alloy 230 for IHX-A and Alloy 800H for IHX-B) and further evaluating technology needs (including new consideration of thin section and grain size effects and joining technology development), we are ready to modify our earlier recommendations pertaining to materials. There is now general agreement within our study that Alloy 617 be selected for the high-temperature (760-950°C) IHX-A and that Alloy 800H be used for IHX-B with a maximum temperature of 760°C.

The rationale for selection of Alloy 617 over Alloy 230 is as follows. The selection of one versus two alloy candidates for IHX-A basically halves the resources that need to be directed to technology needs for this component (see Table 2-3 in Section 2.1.4). The prime technical reason for the selection is the much higher 950°C creep resistance of Alloy 617. Almost all other factors including service experience, expected service life, product availability, and maturity of databases for ASME Code qualification would also favor the use of Alloy 617. Expected corrosion performance of the two alloys is about equivalent. The only potential downside to Alloy 617 relative to Alloy 230 is that the former contains Al+Ti over a specification-allowed range of 0.8-2.1% and high levels of Al+Ti are sometimes detrimental to the ease and efficiency of brazing. The ordinary solutions for this were discussed in Section 2.1.3.2. Therefore, the potential effect on brazing of the Al+Ti content of Alloy 617 is not expected to be significant. However, it is acknowledged here for completeness.

Alloy 800H is the logical selection for IHX-B with a maximum temperature of 760°C. As noted earlier, it is one of the few alloys covered in ASME Section III, Subsection NH. Its two potential competitors in this regard are 304 and 316 stainless steels. Although both are qualified to a higher temperature (816°C) in Subsection NH, their strengths and high temperature oxidation resistance are inferior to those of Alloy 800H. Although some technology needs were identified for Alloy 800H in Table 2-3, the extent of those needs is much less than those identified for Alloy 617 or Alloy 230.

2.2 Materials Lifetime

In the functions and requirements identified as the basis for this study (see Section 1.2), the nominal design lifetime of the NGNP is specified to be 60 years. At the target reactor outlet temperature of 950°C, it is anticipated that the design life of a metallic IHX will be shorter, presently specified in the functions and requirements to be a minimum of 10 years. There are at least three materials related considerations that would potentially limit the lifetime of the IHX. These are creep and fatigue, related to steady-state and transient conditions at high temperature, plus "corrosion" effects associated with trace impurities that are likely to be present within the PHTS and SHTS helium working fluids. To provide a basis for evaluating the effect of transients, two surrogate transients have been identified in the functions and requirements of Section 1.2. These are startup and shutdown (600 occurrences), which is a normal operation transient, and loss of secondary pressure (LOSP) (one occurrence), which is a design basis event (DBE).

The materials lifetime limitations associated with steady-state and transient events are addressed in Sections 2.2.1 through 2.2.3. An overall assessment of the effect of temperature on materials properties is provided in Section 2.2.4. Corrosion-related effects are addressed in Section 2.2.5.

The creep and fatigue assessments provided in Sections 2.2.2 through 2.2.3 are intended only to determine the appropriateness of the construction and materials to the IHX applications. They do not constitute a quantitative life assessment of the components. Those conclusions will follow a comprehensive program that includes material testing, thermo-structural analysis and component validation testing. Not considered in the present assessments are the combined effects of creep and fatigue on thermal cycles, an interaction best addressed by analyses that include creep history and its influence on strain. These analyses are comprehensively covered in ASME III, Subsection NH, Non-mandatory Appendix T, for Alloy 800H at least. A similar approach can be used for Alloy 617, utilizing the draft code case rules.

2.2.1 Normal Operation Life Estimates Based on Creep Properties

The IHX is presumed to be a series configuration, with a high-temperature-capable heat exchanger (IHX A) and a second heat exchanger (IHX B) operating at a more moderate temperature to complete the requisite heat exchange. This arrangement allows selection of materials specific to the environmental demands of each. For the IHX-A the material choice is Alloy 617, while IHX-B is to be of Alloy 800H construction.

The primary flow circuit is assumed to be internal to the unit-cells. With the higher-pressure secondary circuit outside the pressure boundary, cells are nominally in a compressive state. The exception to this is a design-basis event, assigned a probability of 10^{-2} to 10^{-4} per plant year, in which there is a complete loss of secondary pressure. During that event, hydraulic loading on the cell reverses and is greatly increased in magnitude until gas on the primary side can be evacuated to restore balance. Consequences of this event for the IHX are discussed in Section 2.2.3.

Pressure acting on the unit-cells produces stress on internal, primary-side, fins seen in Figure 2-1. The thermal design for IHX-A specifies 1692 fins per meter, with 0.102-millimeter fin thickness, or 17.3% solid metal through the fin. Nominal hydrostatic loads on the hotter ends of IHX-A and IHX-B are 0.219 and 0.343-MPa respectively. These pressures, acting on the exposed inner surfaces of the parting sheets are borne by the fins with plain stresses indicated in Table 2-4

. Stresses are calculated based on the solidity of the section only. As such they do not include other possible geometric effects or mechanical loads yet to be determined by system-level analysis.

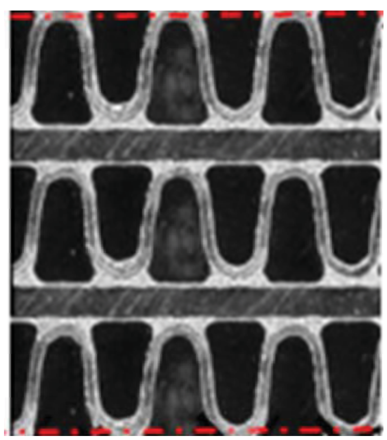


Figure 2-1 Photograph of Example Plate-Fin Heat Exchanger Cross-Section

Table 2-4 IHX Internal Fin Stress-Temperature States

	Nominal Operation	
	IHX A	IHX B
Differential Gas Pressure, MPa	0.219	0.343
Stress (P/A), MPa	1.05	1.64
Metal Temperature, ˚C	950	760

Typical creep data, excerpted from Manufacturer's brochures (Refs. 2-11 and 2-13) and shown in Figure 2-2, were reviewed for Alloy 617 for IHX-A and Alloy 800H for IHX-B.

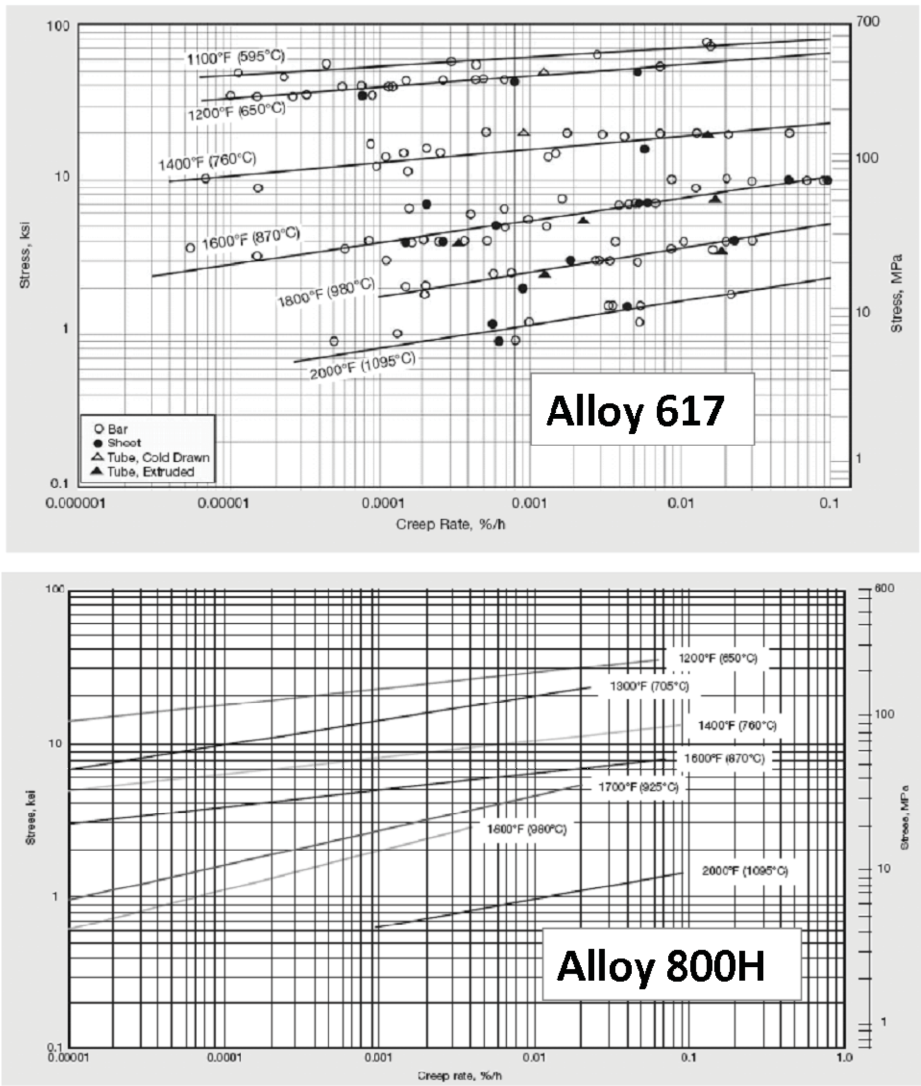


Figure 2-2 Typical Temperature-Dependent Creep-Rate Data for Alloy 617 and Alloy 800H

The NGNP IHX has a service life of 60-years, or approximately 525,000-hours. Manufacturer's data are limited to creep rates of 0.00001%/hr; or 100,000 hrs to 1% creep-elongation. Data were, therefore, extrapolated assuming power-functions, and compared with conditions and requirements in Table 2-5. Both heat exchangers, under the assumptions of this study, show adequate creep-life to meet a 60-year lifetime under normal operating conditions.

Table 2-5 Creep-Life Assessment for IHX-A and IHX-B

	IHX-A – Alloy 617		IHX-B – Alloy 800H	
Condition	Normal	Reference	Normal	Reference
Temperature	950˚C	980˚C	760˚C	760˚C
Stress	1.05-MPa	6.8-MPa	1.64-MPa	29.0-MPa
Time to 1% Creep	>525,000-hr	525,000-hr	>525,000-hr	525,000-hr
Compliance	Meets Requirement		Meets Requirement	

2.2.2 Startup and Shutdown Transient Assessment

Low-cycle fatigue can control the lifetime of a heat exchanger in terms of pressure, thermal stress, or both. Under normal operation, the pressure balance between the two streams is controlled to a level where pressure-induced fatigue for the 600 maximum start-stop cycles is negligible. Thermo-mechanical stress in the IHX must however be addressed.

A start-up and/or shut-down cycle for the PBMR is assumed to occur over a period of approximately 9 hours. For a heat exchanger with a time constant on the order of tens-of-minutes, the startup transient may be considered quasi-steady. The same logic applies to a controlled shut-down as well. Thermo-mechanical fatigue for this study is therefore assessed for the alternating stress between room-temperature-isothermal and design-point operating states.

The finite-element model of IHX-A, shown in Figure 2-3, was constructed for this purpose. IHX-A was chosen for its more demanding conditions.

The model takes advantage of the unit-cell's symmetry by analyzing one-half of the cell and applying appropriate boundary constraints. Fins are modeled as solids with orthotropic thermal and stiffness properties extracted from detailed fin models. These provide the correct interaction with the parting sheets in which the object thermal stress resides.

Imposing the resulting temperature field on the structure produces the results seen in Figure 2.2-4. The maximum stress-intensity of 40.9-MPa will relax by creep, while dwelling at operating conditions, until a controlled shutdown returns the structure to a room-temperature isothermal state. The stress-state at shutdown will be reversed, but at room-temperatures, the magnitude indicates that stresses will remain in the elastic range. A subsequent controlled return to the operating state simply restores stresses to the relaxed state existing prior to shutdown. By not exceeding the elastic limit at shutdown, fatigue damage does not accumulate in the heat exchanger core.

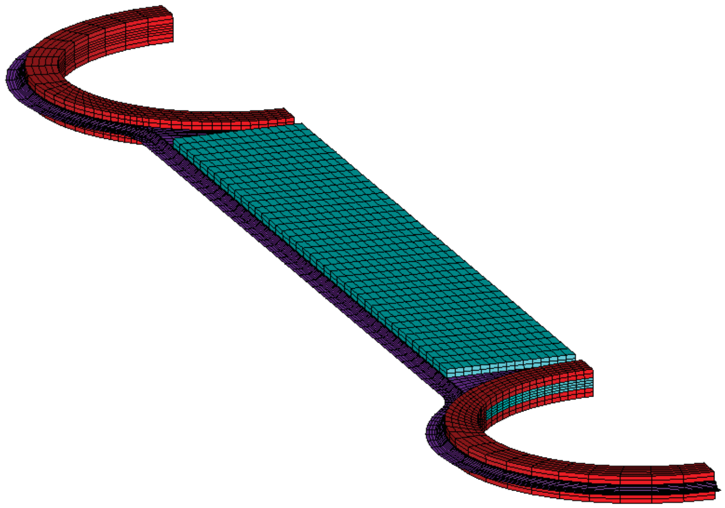


Figure 2-3 Finite-Element Model for Evaluation of Unit Cell Thermo-Mechanical Fatigue

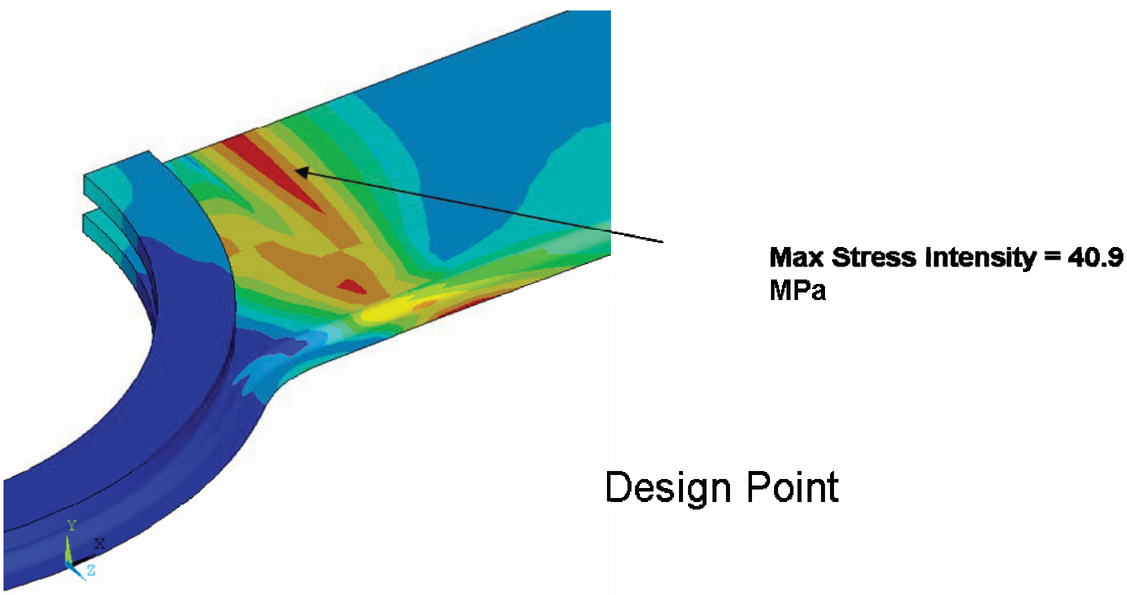


Figure 2-4 Design Point Thermo-Mechanical Stress State of IHX-A Unit-Cell

2.2.3 Loss of Secondary Pressure

Of the transient maneuvers, only the loss-of-secondary pressure is expected to pose a challenge to the Unit-Cell IHX. The differential-pressure magnitude at the highest temperature regions increases from 220-KPa to 9-MPa during the event. Without a more refined definition, the transient is assumed to be a step-function change in pressure and flow. Furthermore, metal temperatures are assumed to be the peak operational gas temperature. The event, in reality, is unlikely to be instantaneous. With a large volume of gas escaping from a finite sized breech, the pressure loss should be much more gradual. Because large temperature differences will exist in the heat exchanger at the initiation of the event, thermal conduction and free convection will be active modes of heat transfer tending to lower peak temperatures. Assumptions are therefore conservative, yielding preliminary conclusions more pessimistic than can be expected from a more refined analysis of system and IHX behavior during a loss-of-secondary-pressure event.

Consideration has been given to the coupling arrangement to the IHX. This matters little to the thermal performance of the IHX, but whether the SHTS is coupled to the inside or outside has a bearing on the behavior of the IHX if pressure loading becomes largely unbalanced with the loss of SHTS pressure. If assigned to the outside, the depressurization will produce an expanding hydrostatic load; a collapsing load will result if it is assigned to the internal pass. Elastically calculated stress magnitudes and locations will be similar for both, but the eventual failures at 950°C may be very different.

Creep-rupture life during a loss of secondary pressure is estimated as the time for the internal fins supporting the pressure boundary to rupture in a purely tensile or compressive field at 9-MPa and at a metal temperature equal to the local peak gas temperature. For IHX-A, that temperature is 950°C; for IHX-B it is 760°C. Alloy 617 and Alloy 230 are evaluated as alternatives for IHX-A and Alloy 800H, alone, was considered for IHX-B

IHX-A Internal Fin Creep-Rupture Life – Loss of SHTS Event

Creep rupture data for Alloy 617 is used from Reference 2-11 in the form of a Larson-Miller Parameter (LMP) plot. A similar plot is made for Alloy 230 using manufacturer's data (Ref. 2-12). Equations are generated from these plots are reduced to the form of a power-function for LMP as a function of stress:

$$LMP = A\sigma^{B}$$

The time to rupture is a function of temperature and LMP, and is expressed in the general equation,

$$t_{RUPTURE}(hr) = 10 \cdot e^{[LMP/T(K) - 20]}$$

with coefficients for IN617 and H230 presented in Table 2-6.

Table 2-6 Coefficients for Power-Function, LMP = *f(σ)*

	A	B
Inconel Alloy 617	45269	-0.1327
Haynes Alloy 230	36492	-0.0964

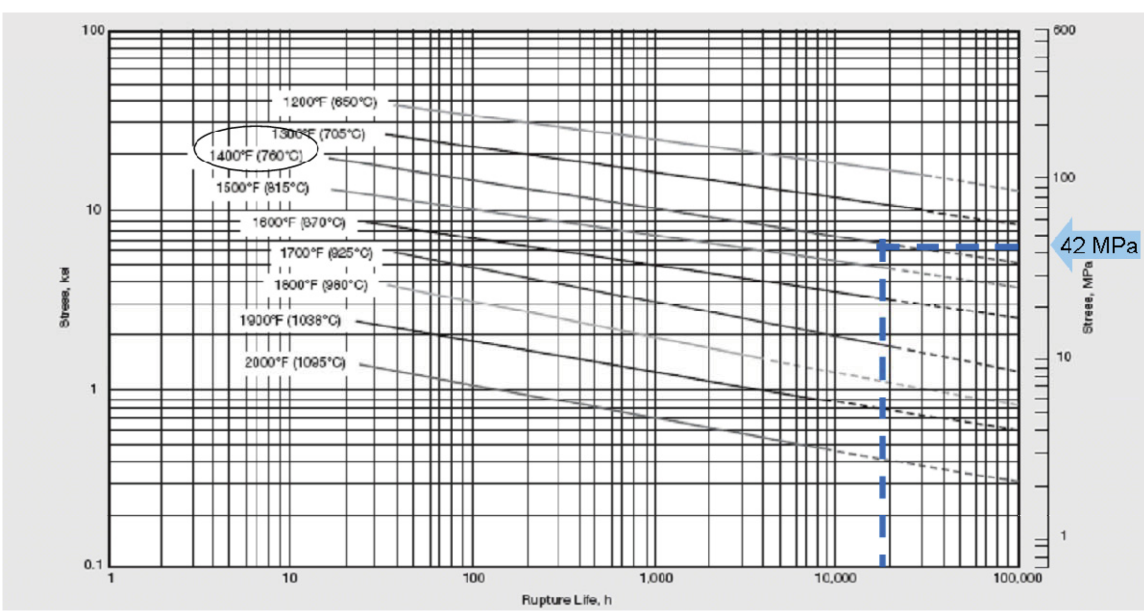
The thermal design for IHX-A specifies 1692 fins per meter, with 0.102-millimeter fin thickness, or 17.3% solid metal through the fin. Direction, of course, depends on whether pressure is lost within or outside the heat exchanger cells.

The resulting times to fin creep-rupture during a loss-of-secondary-pressure event are:

- Alloy 230 - 42 hours
- Alloy 617 - 340 hours

Data for Alloy 800H, at the assumed maximum metal temperature of 760˚C, are presented directly in Figure 2-5 (Ref. 2-13). Having the same fin-thickness, fin-density and assumed pressure during the event as IHX-A, the stress can be assumed to be the same as well. As seen in Figure 2-5, this leads to a predicted rupture life greater than 10,000-hours. Creep damage to the fins in a loss-of-SHTS-pressure event on IHX-B is clearly negligible.

Figure 2-5 Creep Data for Alloys 800, 800H and 800HT



2.2.4 Influence of Operating Temperature

Consideration is given in this section to how maximum operating temperature might affect the choice of the IHX configuration (i.e., single unit versus split high temperature/low temperature units), planned or anticipated lifetimes of the IHX units and limiting factors, and candidate materials. Further, for each material/temperature combination, technology development needs are highlighted.

The first row in Table 2-7 lists IHX arrangement options as a function of temperature in 50°C increments from 750°C to 950°C. A single IHX unit utilizing a single alloy appears feasible and preferred for full life operation at temperatures of 750°C and 800°C, and might be viable for operation at 850°C. However, the split unit with a high-temperature IHX A and a lower temperature IHX B will almost certainly be required for 900°C and 950°C operation. In these latter two cases, the goal is to have a high-temperature IHX capable of at least 10 years and a full life IHX B at a maximum temperature of 760°C.

The third row of the table provides recommended materials options for each of the temperatures under consideration. Alloy 800H, which is included in ASME Section III for temperatures up to 760°C, is given as the single option for 750°C operation. The Hastelloy XR and Alloy 617 materials would also certainly work for full life at this temperature but would be much more expensive solutions and would also require incorporation into ASME Section III. Additionally, the vast majority of the database for Hastelloy X rests with the Japanese gas-cooled reactor program and arrangements would be needed to gain access to this information.

All three of the alloys listed would likely be suitable for full life operation at 800°C but all would require ASME Section III code action. Both Hastelloy XR and Alloy 617 could potentially provide full life in a single unit IHX at 850°C, or at least an IHX unit with a life exceeding 20 years. For operation at either 900°C or 950°C, Alloy 617 is to be chosen over Hastelloy XR for IHX A on the basis of strength (see later discussion) and Alloy 800H is selected for IHX B for a temperature not to exceed 760°C.

Rows 4 through 8 of Table 2-7 indicate where some technology developments remained to be filled. For example, ASME Section III Code action is required for all the listed materials at temperatures of 800°C and up. As noted previously, only Alloy 800H has Section III approval and then only to 760°C. Earlier discussions of joining of compact heat exchange cores (brazing and diffusion bonding) and considerations of potential grain size and thin section effects make it clear that there are information and data needs associated with these areas. This is true for all temperatures of operation given in the table. Under the parameters of “some general properties data” and “aging and environmental effects data”, some further developments are likely desirable for all material/temperature combinations except for Alloy 800H at 750°C.

Table 2-7 IHX and Materials Options as a Function of Temperature

Parameter	Maximum Operating Temperature (°C)				
	750	800	850	900	950
IHX Arrangement Options	Single IHX	Single IHX	Single IHX or IHX A & B	IHX A and IHX B	IHX A and IHX B
Goal Lifetime	Full	Full	Single IHX – full IHX A >20 y IHX B - full	IHX A > 10y IHX B - full	IHX A >10y IHX B- full
Recommended Materials Options	Alloy 800H*	Alloy 800H, Hastelloy XR Alloy 617	Hastelloy XR or Alloy 617 for single IHX and IHX A, Alloy 800H for IHX B	Alloy 617 for IHX A, Alloy 800H for IHX B	Alloy 617 for IHX A, Alloy 800H for IHX B
ASME Code Action Needed	No	Yes for all	Yes for Hastelloy XR and Alloy 617	Yes for Alloy 617	Yes for Alloy 617
Brazing and Diffusion Bonding Data Needed	Yes	Yes for all	Yes for all	Yes for both	Yes for both
Grain Size & Thin Section Data Needed	Yes	Yes for all	Yes for all	Yes for both	Yes for both
Some General Properties Data Needed	No	Yes for Hastelloy XR and Alloy 617	Yes for Hastelloy XR and Alloy 617	Yes for Alloy 617	Yes for Alloy 617
Aging and Environmental Effects Data Needed	No	Yes for Hastelloy XR and Alloy 617	Yes for Hastelloy XR and Alloy 617	Yes for Alloy 617	Yes for Alloy 617
Corrosion Allowance Relative to Temperature	Strongly dependant on temperature, coolant impurities, and alloy. See discussion in Section 2.2.5				
Nominal 1000 h Creep Rupture Strength** (MPa)	800H = 70 Hast XR = 100 617 = 172	800H = 55 Hast XR = 80 617 = 110	800H = 41 Hast XR = 50 617 = 69	800H = 28 Hast XR = 32 617 = 50	800H = 17 Hast XR = 20 617 = 32

* Included in ASME Section III to 760°C

** The calculated creep-rupture life of Alloy 617 at 950°C and a stress loading of 42 MPa was 340 hours. The stresses noted here provide a relative comparison for rupture in 1000 hours for all alloys at all temperatures considered.

The extent of data generation needed for any of the materials depends on what additional data are required to provide an acceptable database for an ASME Section III Code submittal. Considerable information exists on the aging behavior of all of the alloys but much less is available in the area of corrosion in impure helium. Technology development requirements will be discussed more fully in Sections 2.3 and 4.

The next-to-last row in Table 2-7, "corrosion allowance relative to temperature", is of such potential importance that it is addressed in a separate section (Section 2.2.5) to follow.

The final row in the table provides nominal values of stress to produce creep-rupture in 1000 hours for each material at each temperature. It was shown earlier in this section that the 42 MPa stress associated with a depressurization of the SHTS could be sustained for >300 hours at 950°C. Although this is already a very conservative result, a 1000-hour life before rupture at this stress would be a very convincing value for survival of the depressurization event. In that regard, Alloy 800H has suitable creep strength for use to 800°C and perhaps 850°C. The strength of Hastelloy XR would support its use through 850°C and probably 900°C. Finally, Alloy 617 appears to have sufficient creep resistance at all temperatures under consideration.

2.2.5 Corrosion Limitations

The corrosion behavior of Fe-, Fe/Ni-, and Ni-base alloys in predicted operating environments for various gas-cooled reactors with helium coolant has been studied worldwide for more than three decades. Summaries of this research can be found in a large number of documents including References 1-1 and 2-14 through 2-16. Studies typically have been conducted at temperatures up to 1000°C in helium doped with low levels of H_2, H_2O, CO, CO_2, and CH_4. Various methods including premixed cylinders, recirculation loops, and once-through loops have been employed to provide the simulated gas-cooled reactor helium. However, significant variations in behavior have been observed related to details of the experimental procedure.

These studies have provided significant insights into oxidation, carburization, and decarburization behavior as functions of alloy chemistry, gas chemistry, and temperature. In particular, perceived protective behavior of alloys is now most often described in terms of carbon activity and oxidation potential. Based on this, one is able to make predictions as to what environments (gas species and their levels and ratios) should provide protective behavior and at what temperatures. This is all well and good until one attempts to determine "corrosion allowances" for our materials on interest, Alloy 617 and Alloy 800H, in particular. What few quantitative data that appear to exist are almost always in the form of corrosion weight gains or losses. The translation of these data to a "corrosion allowance" is at best a poor idea since it cannot give us information on internal oxidation or alloy element depletion. The data are somewhat indicative of the rate of oxide scale formation, but only up to the point that scale loss begins to occur by spalling and/or dissociation.

The formation of a protective oxide scale with parabolic rate behavior is, of course, essential to the oxidation resistance of the base metal. If the scale is non-protective, oxidation will proceed at a linear rate dependant on temperature and the level of oxidants in the environment. The degree of protectiveness will also influence the degree and depth of internal oxidation and the propensity for carburization/decarburization. The alloys we are considering tend to form a protective Cr_2O_3 oxide file. The useful lifetime of a structure from a corrosion viewpoint is, then, dependant on providing a supply of Cr sufficient to maintain the Cr_2O_3 scale. The diffusion of Cr from the metal to oxide-metal interface or oxide-environment interface will result in a concentration gradient of Cr and, theoretically its total depletion. Unfortunately, we do not now know the level of Cr that is necessary to maintain the protective scale, but Reference 2-17 shows that, for Fe-Cr alloys, the rate of oxidation increases very rapidly for 18% Cr and less. Further, we do not know how the rate of Cr depletion is influenced by alloy chemistry, gas chemistry and temperature. If the protective scale cannot be supported, the corrosion rate of the alloy will accelerate and become very large, internal voids will form, and mechanical properties will deteriorate rapidly. Finally, can the total Cr source influence corrosion-based useful lifetime? For example, a section of "infinite" thickness should, if diffusion rates are sufficient, provide Cr to the Cr_2O_3 scale for "eternity". On the other hand, the Cr in a section only a few microns thick would be exhausted almost immediately.

As a first try at exploring "corrosion allowances" for the materials of our compact heat exchanger, we have taken data produced recently by the CEA (Ref. 2-7) for Alloy 617, Alloy 800H and Hastelloy X, and by GE for these same alloys in about 1980 (Ref. 2-18). Metallography of the exposed materials was used to take measurements of scale thickness, depth of internal oxidation and a carbide-free depth. This is referred to as an affected depth by CEA and a Cr-depleted depth by GE (i.e., no Cr = no or reduced carbides). The CEA data were from a single ~800 hour exposure at 950°C; data by GE were obtained from exposures at 750°C through 950°C for exposure times up to 10,000 hours.

The only "direct" comparison that can be made between the two data sets is demonstrated in Table 2-8. Remember, though, that the alloys tested were from different heats of material. For Alloy 800H the oxide scale thicknesses shown from CEA and GE are 6 μm and 1.4 μm, respectively. No comparison is available for the depth of internal oxidation although it is considerable (38μm) in the material tested by CEA. Depletion depths for Cr were measured as 80 μm and 43 μm, respectively. (A much better definition of Cr depletion would be related to measured compositional gradients. Unfortunately, these are not available here.)

The CEA and GE data for oxide scale thickness and Cr depletion for Alloy 617 are quite comparable. The internal oxidation depth of 16 μm provided by CEA for Alloy 617 is considerably less than that seen for Alloy 800H; there is no GE data for depth of internal oxidation. Oxide scale thicknesses and the Cr depletion depths for Hastelloy X from the two data sources are in relatively good agreement. No internal oxidation was observed in the Hastelloy X from the CEA tests and this is consistent with the behavior of modern variants such as Hastelloy XR. Hastelloy X materials available at the time of the GE studies are known to undergo internal oxidation.

Table 2-8 950°C Results, CEA* (800 h) and GE (1000 h)**

Alloy	Affected Depth (μm)					
	Oxide Scale		Internal Oxidation		Cr Depletion	
	CEA	GE	CEA	GE	CEA	GE
800H	6	1.4	38	-	80	43
617	5	3	16	-	65	71
Hast. X	2	2	0	20	30	21

* CEA environment – 200 H_2, 2 H_2O, 50 CO, 20 CH_4 (μatm), balance He
** GE environment – 400 H_2, 2 H_2O, 40 CO, 20 CH_4, 0.2 CO_2 (μatm), balance He

Metallographic measurements from a number of specimens exposed in the GE study were used to predict cumulative, quasi steady state corrosion rates for Alloy 800H, Alloy 617, and Hastelloy X at temperatures of 750°C, 850°C, and 950°C. The results of these predictions are shown in Table 2-9 through Table 2-11. The results are worrisome and often contradictory as further explained below.

At 750°C (Table 2-9) oxide scale thicknesses measured after 1000 h, 3000 h, 6000h, and 10000 h result in predictions of scale formation rates of 2 to 18 μm/y, depths of internal oxidation of 7 to 88 μm/y, and depths of "Cr depletion" of 6 to 210 μm/y depending on alloy and length of exposure. Note that the predicted rates (μm/y) decrease dramatically with the length of exposure. This is not surprising and presumably indicates that the protectiveness of the oxide scale is increasing as time progresses (i.e., oxidation is progressing in a parabolic fashion). Further, the rates are essentially "linear" rates between time zero and the exposure time. Rates appear to have reached a "steady state" based on the 6000 h and 10000 h exposures but there is no way to know with certainty whether they will change further at longer times. Given the very large differences in predicted rates based on 1000 h and 3000 h data versus that for the longer exposures, one might also have questions as to whether the environmental conditions for the shorter and longer exposures were equivalent. The relative corrosion resistances of the alloys at 750°C from best to worst is Hastelloy X, Alloy 617, and Alloy 800H. However, the latter two appear almost equivalent.

Table 2-9 Results of GE 750°C Exposures in 400 H_2, 2 H_2O, 40 CO, 0.2 CO_2, 20 CH_4 (μatm), Balance He

Alloy and Time Basis	Rate (μm/y)		
	Oxide Scale	Internal Oxidation	Cr Depletion
Alloy 800H			
1000 h	18	53	140
3000 h	9	26	210
6000 h	6	18	34
10000 h	4	8	35
Alloy 617			
1000 h	9	35	105
3000 h	9	32	70
6000 h	3	16	26
10000 h	4	11	21
Hastelloy X			
1000 h	18	88	88
3000 h	6	15	-
6000 h	3	9	6
10000 h	2	7	8

Table 2-10 shows rate predictions for all three alloys based on 1100 h, 3000 h, 6000 h, and 10000 h exposures at 850°C. Predicted rates of scale growth are large based on the shorter time exposures, but their variations with alloy are about as would be expected. For the longer-term exposures, rates reduce to more reasonable values. This is also true for the rates of internal oxidation and Cr depletion for all of the alloys. Except for Hastelloy X, even the rates based on the longer exposures are considerably higher at 850°C than at 750°C. What is most surprising from the 850°C data set is that the corrosion performance of Alloy 800H appears to be superior to that of Alloy 617.

Table 2-10 Results of GE 850°C Exposure 400 H_2, 2 H_2O, 40 CO, 0.2 CO_2, 20 CH_4 (μatm), Balance He

Alloy and Time Basis	Rate (μm/y)		
	Oxide Scale	Internal Oxidation	Cr Depletion
Alloy 800H			
1100 h	56	111	175
3000 h	19	51	70
6000 h	13	28	40
10000 h	8	16	24
Alloy 617			
1100 h	28	76	80
3000 h	16	63	128
6000 h	9	29	88
10000 h	6	22	62
Hastelloy X			
1100 h	20	76	96
3000 h	9	26	50
6000 h	7	20	23
10000 h	4	11	14

Predictions of rates from the final data set (1000 h, 3000 h, and 5500 h at 950°C) are given in Table 2-11. First, note that the rates for oxide scale formation are in general lower than those shown above for 850°C and, indeed, are closer to the 750°C predictions. Does this indicate possible differences in experimental parameters or is it indicative of oxide spalling or dissociation at this higher temperature? The predicted rates for internal oxidation and Cr depletion are quite significant for all alloys, especially for Alloy 617. Earlier, in Table 2.2.5-1, it was shown that the depth of Cr depletion for Alloy 617 was equivalent for the CEA and GE exposures at 950°C. On the other hand, the GE data for Alloy 800H showed a lower depth of depletion than did that from CEA, even lower than that for Alloy 617. The situation relative to the corrosion resistance of these two alloys remains clouded. However, all of the predictions for Hastelloy X appear consistent with those from the lower temperatures.

Table 2-11 Results of GE 950°C Exposure 400 H_2, 2 H_2O, 40 CO, 0.2 CO_2, 20 CH_4 (μatm), Balance He

Alloy and Time Basis	Rate (μm/y)		
	Oxide Scale	Internal Oxidation	Cr Depletion
Alloy 800H			
1000 h	12	-	377
3000 h	25	93	175
5500 h	6	20	127
Alloy 617			
1000 h	18	-	622
3000 h	15	83	339
5500 h	3	-	-
Hastelloy X			
1000 h	18	145	184
3000 h	15	88	146
5500 h	8	35	-

Weight gain data in terms of mg/cm^{2}sec cumulative rate are shown in Table 2-12 for all alloys at all temperatures for 1000 h, 3000 h, and 10,000 h exposures. It is essentially impossible to make quantitative predictions from these data as to the corrosion phenomena (scale thickness, etc.) discussed above. However, the decrease in weight gain rates with exposure time shown for 750°C and 850°C is consistent with the buildup of an increasingly protective surface oxide. The data from the 950°C exposures are even more difficult to interpret but surely indicate that the surface oxides have begun to spall and/or dissociate.

An additional source giving predictions of corrosion allowances for Alloy 617 and Alloy 800H is provided in Reference 2-19 from Westinghouse Reaktor GmbH. Their predictions are based on exposures conducted in the HHT project for up to 9000 h at temperatures to 900°C. The exposure environment was 50 H_2, 5 H_2O, 50 CO, 5 CO_2, 5 CH_4, 5 N_2, balance He (in μbar). They used weight gain to predict oxide scale thickness, defined as δ, and metallographic and microprobe measurements to assess depths of internal oxidation and Cr depletion. It was observed that the depth of internal oxidation was nominally 3δ to 6δ and that Cr was usually depleted to a depth of 6δ. Predicted corrosion allowances, extrapolating from ~1 year (9000 h) to 36 years of reactor operation on a $t^{1/2}$ (time) basis, are given in Table 2-13.

Table 2-12 GE Weight Gain Rates (10^{-7} mg/cm^{2}sec) from Exposures at 750°C through 950°C

Alloy	Exposure Time (h)		
	1000	3000	10000
750°C			
Alloy 800H	1.72	0.48	0.20
Alloy 617	1.25	0.51	0.22
Hastelloy X	1.39	0.15	0.07
50°C			
Alloy 800H	1.87	0.91	0.34
Alloy 617	1.66	1.25	0.44
Hastelloy X	2.06	0.56	0.26
950°C			
Alloy 800H	0.21	0.54	0.09
Alloy 617	0.41	1.15	0.07
Hastelloy X	0.64	0.95	0.37

Table 2-13 Predicted Corrosion Allowances for 36 Years

Temperature (°C)	Corrosion Allowance (μm)	
	Alloy 617	Alloy 800H
900	800	740
800	300	280
675	70	60

One can, of course, calculate an "average" rate in μm/y and, although the rate will be underestimated in the short term, over the long term this will be a fairly good estimate. For Alloy 617 at 900°C, for example, the calculated rate is 22μm/y. There are no one-to-one comparisons available for the CEA versus Westinghouse data or for Westinghouse versus GE. However, it appears that Westinghouse predicts lower rates of corrosion. Again, one must consider that exact alloy heats, test conditions, and environments can have significant effects on results.

All of the "corrosion factors"discussed above could place limits on the effective lifetime of IHX heat exchange cores. This is especially true in the case of the plate-fin compact type unit because of the associated very thin material sections. In the current plate-fin design, the fin sections are constructed of foils of only 0.102 mm (102 μm) thickness, while the plates are 0.380

mm (380 μm). The plates in the PCHE design are typically >0.5 mm (>500 μm) but have flow channels of about one-third of the plate thickness, reducing the effective thickness to a value comparable to the plates in the plate-fin design. Although the fin thickness in the plate-fin design appears to be perfectly adequate to resist creep and fatigue loadings under both normal and depressurization conditions (see Sections 2.2.1 through 2.2.3), the lifetime calculations did not include consideration of a "corrosion allowance". The data and predictions presented above provide a rather sobering revelation in this regard. It can be seen for 950°C that the predicted depths of internal oxidation could approach or exceed material thickness after only a very few years of exposure. Of even more immediate concern is that predicted rates of Cr depletion at 950°C indicate a useful corrosion life, based on Cr supply, of less than one year for 0.102 mm thick material. Further, the above is based on a primary side corrosion evaluation only. How corrosion proceeds on exposure to the secondary side helium is unknown at present. The predicted rates of corrosion at the lower temperatures are not quite so restrictive but are still an area of concern. In any event, final designs with thin sections will, of necessity, be forced to include "corrosion allowances" taking into consideration the phenomena discussed above and their potential to affect load carrying ability over the long term at high temperatures.

The data and resulting predictions discussed above are a bit more pessimistic than had been expected. It is not known whether this is the result of shortcomings in conduct of the CEA and GE tests or is inherent with these materials under these exposure conditions. It is critical to conduct new well-controlled experiments to determine scale thicknesses and depths of internal oxidation as a function of time (at least for 500 h through 10,000 h) at temperatures from 700°C to 1000°C (as appropriate for the alloy application). These determinations can be made by metallography. (The effect of such internal oxidation on properties is also very important to determine.) Although a Cr depleted depth can be inferred by metallography, a much better procedure will be to determine the Cr composition gradient from the surface inward and how this might affect properties within this zone and continued availability of Cr to the oxide

Corrosion exposures should be performed in "all" expected environments. This would include the environment predicted for the NGNP primary circuit and expected possible variations around the chemistry of the NGNP environment. Determination of corrosion phenomena associated with the much cleaner secondary side helium is also necessary. Perhaps tubular specimens could be utilized to look at primary and secondary side environments simultaneously.

2.3 Materials Technology Development

2.3.1 Basis for Technology Development

This section of the report provides a brief summary of materials technology development activities that are prerequisite to the application of specific metallic alloys in the cores of compact heat exchangers. The assumptions leading to the identification of these technology development areas are:

- The primary circuit helium temperature at the entrance to the IHX is 950^{o}C.
- The primary circuit helium contains levels of impurities that will lead to corrosion.
- The IHX is composed of two separate sections, IHX A and IHX B.
- Primary circuit helium exits IHX A at <760^{o}C and enters IHX B.
- Secondary circuit helium exits IHX A at 900^{o}C.
- The design lifetime for IHX A is >10 years and it is designed to be replaceable.
- The design lifetime for IHX B is 60 years.
- The material for IHX A is Ni-base Alloy 617.
- The material for IHX B is Fe/Ni-base Alloy 800H.

2.3.2 Areas of Technology Development

Technology areas that need to be addressed for IHX materials include the following:

- General mechanical properties.
- Brazing and diffusion bonding process development.
- Effects of joining methods on properties.
- Effects of thermal aging on selected properties.
- Effects of environmental exposure on selected properties.
- Effects of grain size on properties.
- Effects of section thickness on properties.
- Corrosion rates in NGNP helium.
- ASME Code Qualification.

Except for brazing/diffusion bonding process development, which has been thoroughly discussed earlier (see Section 1.9.2), all of the technology areas are related to mechanical properties or, to a lesser extent, thermal/physical properties and their application to the ASME Code or detailed component design. The "effects on properties" questions will be discussed further below. Note also that corrosion rates in impure helium and associated corrosion allowances are a part of the environmental effects area.

Alloy 617 is not currently included under Section III of the ASME Codes and a request for its inclusion will need to be generated. In the process of preparation of an ASME Code inquiry for Alloy 617, it is almost certain that specific areas where additional data and information are needed will be identified (e.g., questions of secondary creep). Further, if the requirement is maintained to employ material with small grain size (ASTM grain size number 6 to 8), as opposed to the common Alloy 617 grain size range of ASTM 0 to 3, it will probably be necessary for the ASME Code inquiry to obtain a full range of data for three new heats of material with grain size in the ASTM 6 to 8 range. However, the lifetime assessment given in Section 2.2 indicates that the fatigue life for Alloy 617 of common grain size (ASTM 0 to 3) is more than sufficient to preclude failure by fatigue and, therefore, that the expected improvement to be expected with finer grain size material is not necessary. And, of course, the larger grain size material will have creep resistance superior to that of the fine-grained alloy. The same considerations apply to the properties of Alloy 800H although the specification for this alloy allows material with an ASTM grain size of up to 5 and this should be acceptable in all respects. A possible alternative to the generation of complete data sets for multiple heats of fine-grained materials for Alloy 617 is to use existing data and develop “grain size modification” factors for incorporation into Section III. These factors would be similar to “weldment strength reduction” factors currently employed in some parts of the Code. Similar considerations could be applied relative to possible effects of section thickness on properties.

Alloy 800H is currently incorporated into ASME Section III to a maximum use temperature of 760°C. Therefore, if (as specified in the assumptions in Section 2.4.1) the maximum temperature in IHX B is held to <760°C, it is likely that no further ASME Code action would be required for Alloy 800H, except to extend the allowable stresses to 600,000 h. According to Reference 2-20, there are sufficient data available to justify this increase and to extend the allowable temperature to 900°C.

Data on the effects of joining (welding, brazing, and diffusion bonding) on properties could also be required for the ASME Code inquiry on Alloy 617 and might also be in question for Alloy 800H. This will need to be considered in detail as preparation of the Code package proceeds. In any event, such information needs to be available to the designer to guide component dimensioning and setting of safety factors. Of course, there is considerable information available on properties of welded Alloy 617 and Alloy 800H, but much less experience with diffusion bonded and brazed materials. Arguments can be made that the diffusion bond between identical base metals should result in a homogeneous boundary structure with no differences in properties from the base metals. However, a similar argument cannot be made for a brazed joint. A braze alloy of composition different from the alloy to be joined is employed and there is diffusion of elements into and out of the braze zone. Such compositional and structural differences can result in differences in properties.

Although not currently required for direct input into the ASME Code, it is expected that the designer will consider any effects of long-term thermal aging on properties and, therefore, on allowable stresses. Data available for both Alloy 617 and Alloy 800H indicate that, over the temperature range of interest, there will be no catastrophic changes in properties. Typically, strengths will be increased at the sacrifice of some degree of ductility. However, some additional data would provide a greater degree of comfort in time/temperature areas where data may be sparse. This would be of even greater importance if, for example, the final Alloy 617 specification requires an ASTM grain size number significantly greater than ASTM 3.

The designer also needs to have knowledge of and to incorporate into the design any effects in addition to changes caused by thermal aging that long-time exposure to the “impure” helium environment might produce. These may include:

- Reduction in cross section by scale formation.
- Reduction in effective cross section by internal oxidation.
- Carburization of the base metal.
- Decarburization of the base metal.

The formation of a protective scale with parabolic rate behavior is, of course, essential to the oxidation resistance of the base metal. If the scale is non-protective, oxidation will proceed at a linear rate dependant on temperature and the level of oxidants in the environment. The degree of protectiveness will also influence the degree of internal oxidation and the propensity for carburization/decarburization. Of the items above, protective scale formation will likely have the least effects on materials properties and behavior. Resultant load carrying capability will be reduced only to the extent that the original cross section of the base material is reduced.

Both Alloy 617 and Alloy 800H are known to undergo internal oxidation, primarily of aluminum, when exposed in impure helium at elevated temperatures. The depth to which internal oxidation occurs is a complicated function of alloy chemistry, the impure helium chemistry, protectiveness of the outer oxide scale, temperature and time. The extent to which such internal oxidation influences alloy properties and behavior is not well established, but is almost certainly not beneficial.

Extensive carburization of the base metal is unlikely, unless the oxide scale is relatively non-protective and the carbon activity in the impure helium is quite high. Carburization would, of course, result in a material with improved load carrying capability in the short term, but would even further reduce the protectiveness of the oxide scale by tying up chromium as carbides. At some degree of carburization, concerns would arise as to its effects on ductility and toughness. Decarburization, also unlikely if the oxide scale is protective, would have the opposite effect on properties.

All of the factors above could have importance as to “corrosion limitations” on the effective lifetime of IHX heat exchange cores. This is especially true in the case of the compact plate-fin type of heat exchanger, because of the associated very thin material sections. In the current plate-fin design, the fin sections are constructed of foils of only 0.102 mm thickness. Although this thickness seems perfectly adequate to resist creep and fatigue loadings under both normal and depressurization conditions (see Sections 2.2.1 though 2.2.3), the lifetime calculations do not take into consideration a “corrosion allowance”. The final design with thin sections will, of necessity, be forced to develop such “allowances” taking into consideration the phenomena discussed above and their potential to affect load carrying ability over the long term at high temperatures.

As a final thought relative to corrosion, Hastelloy XR has been shown to have corrosion resistance in impure helium much superior to that of Alloy 617 or of Alloy 800H. A question to be answered, then, is whether the creep strength of Hastelloy XR is sufficient to support its use at 950^{o}C for normal operation and depressurization transients.

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3 HTS OPTIONS

In the preceding Sections 1 and 2, design and materials issues associated with the IHX were assessed in some detail, with emphasis on plate-fin heat exchanger technology. This section continues the evaluation of key HTS components and then focuses on certain design selections of the HTS as a whole. A particular objective is to evaluate the tradeoffs between one and multiple HTS loops.

In Sections 3.1 through 3.3 that follow, additional considerations related to circulators, isolation valves and steam generators are evaluated. Section 3.4 then turns to the system level; looking at the tradeoffs among options for coupling the PHTS fluid to either the "shell-side" or "core-side" of the IHX (the core-side is analogous to the tube-side of a shell-and-tube heat exchanger). Taking all of the above into account, Section 3.5 concludes with an assessment of the number of HTS loops that should be incorporated into the NGNP Conceptual Design.

3.1 Circulator Assessment

The HTS design employs a primary and secondary circulator with the operating conditions as outlined in table below (see also steady state flow sheet, given as Figure 1-2 in Section 1.2).

Table 3-1 Circulator Normal Operation

Circulator	PHTS	SHTS
Circulator Inlet [°C]	337	273
Circulator Outlet [°C]	350	287
Circulator Outlet [kPa]	9000	9100
Circulator Inlet [kPa]	8626	8640
Circulator Pressure Rise [kPa]	374	460
Pressure Ratio	1.04336	1.05324
Circulator Fluid	Helium	Helium
Mass Flow Rate [kg/s]	160	160
Circulator Size[1] [MWe]	11.4	12.5

1: Based on 80% isentropic efficiency and 5 % electric-to-thermal loss

Based on the assumed pressure losses in the PHTS and SHTS, a single-loop will respectively require a 11.4 MWe and 12.5 MWe circulator. In order to reduce the size of the circulator and to enable the use of conventional materials, it is desirable that the circulator inlet temperature be as low as possible. This desire is compatible and consistent with other PHTS optimization objectives, including the reduction of reactor pressure losses by reducing flow and increasing temperature rise across the reactor and the selection of a reactor inlet temperature that allows the use of conventional materials for the reactor pressure vessel. To minimize circulator cost and the need for technology development, it was decided to limit the PHTS circulator inlet temperature to below 400°C.

To date, single-stage radial helium circulators in the 10-12 MWt range have not been manufactured and operated, though it is foreseen that the circulator operating conditions stated in table above will be based on existing technology. Pending circulator conceptual design and economic trade-offs, the PHTS could employ a single radial circulator or multiple parallel radial circulators (single or multi-stage); or alternatively employ a single axial machine. While costs will vary to some extent, none of the envisioned configurations are viewed as feasibility issues.

3.2 Isolation Valve Assessment

Valves support a spectrum of functions, including directing, controlling and preventing the flow of various fluids. Isolation valves, as the name implies, are a specialized subset of valves that perform the latter function. In the context of HTGR applications, such as the NGNP, they may be actuated for planned operating modes and states in a timely manner, as would be the case for maintenance closures, or may be fast-acting in response to an off-normal event. It is important to make clear that this present evaluation is concerned with the fast-acting isolation valves that would respond to an operational event, not the maintenance closure type of isolation valves.

The objectives of this isolation valve evaluation are to review the general use of valves in the preconceptual NGNP design and to evaluate the need for additional fast-acting isolation valves during off-normal events. In addition, as requested by BEA, a survey of isolation valve technology is provided, with particular focus on those related to prior HTGR reactors and programs. The following subsections correspond to each of these objectives.

3.2.1 Review of the Use of Valves in the NGNP Preconceptual Design

Isolation valves are presently located on the two primary interfacing systems of the Secondary Heat Transport System (SHTS), specifically, on the process coupling heat exchanger of the Hydrogen Production System (HPS) and on the steam generator of the Power Conversion System (PCS). The functions of the HPS and PCS isolation valves are to limit the ingress of sulfuric acid and water/steam, respectively, into the SHTS in the event of leaks in the corresponding heat exchangers. The schematic in Figure 3-1 indicates the location of these isolation valves in the reference PBMR NGNP configuration.

As also shown in the figure, there is a SHTS pressure relief valve that separates the high-pressure helium from the ambient environment. The function of this valve is to protect the integrity of the SHTS from internal overpressure.

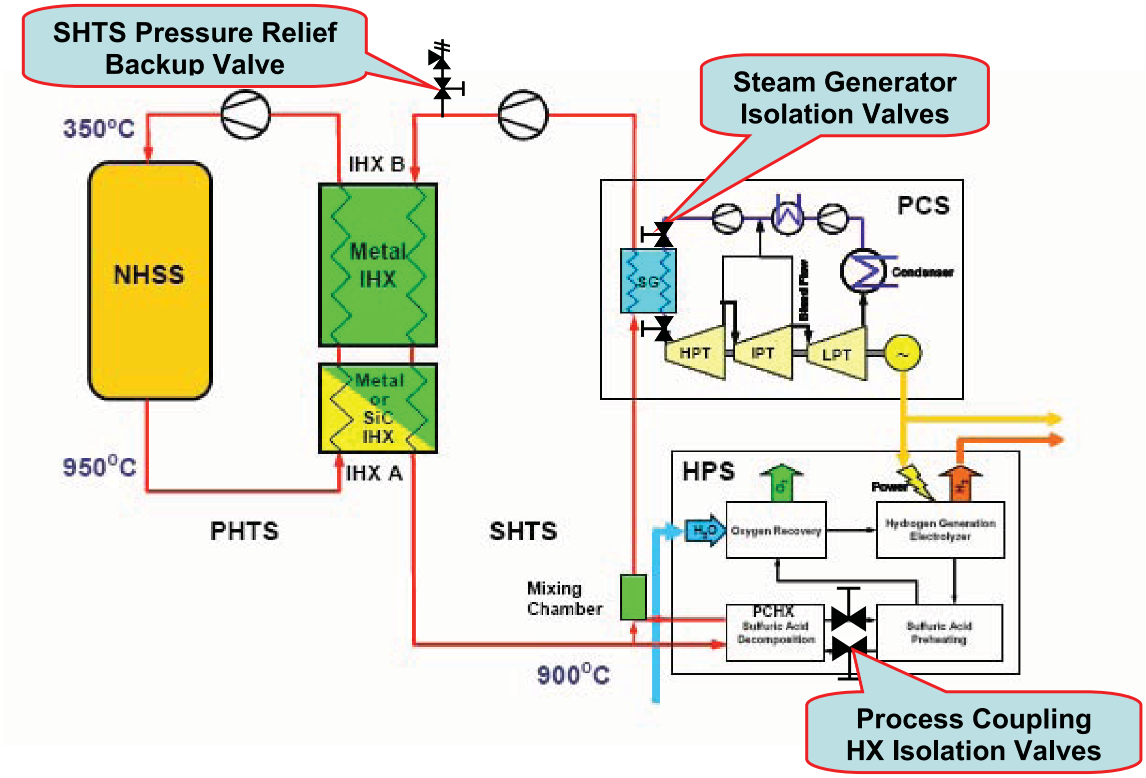


Figure 3-1 Location of Valves in the NGNP

The Primary Helium Pressure Boundary (PHPB) is defined as the pressure enclosing portions of the Primary Heat Transport System (PHTS) and of other systems connected to the PHTS helium volume up to their isolation valves. By this definition, the PHPB incorporates:

1. The Reactor Vessel, including as stated, up to the isolation valves in their connections to other systems,
2. The pressure retaining pipe that leads from the Reactor Pressure Vessel (RPV) to the IHX and the return to the RPV, limited to the outer-most primary coolant pressure retaining pipe where the pipe is multi-walled or annular,
3. The pressure retaining portions of the PHTS circulator and check valve and its connections to services up to their isolation valves,
4. The piping within the IHX Vessel that conducts the PHTS flow to and from the IHX cores, including the IHX Vessel if it provides a boundary for the PHTS fluid,
5. The heat transfer surface of the IHX cores,
6. The pressure retaining pipe that leads from the RPV to the Core Conditioning System (CCS) and the return to the RPV, limited to the outer pressure retaining pipe where the pipe is double-walled, and
7. The pressure retaining portions of the CCS circulator and check valve and its connections to helium services up to their isolation valves.

Figure 3-2 schematically shows the PHPB limits for two cases; one with PHTS helium on the "tube side" of the IHX and the second with PHTS helium on the "shell side".

Similar to the SHTS, there is a PHTS pressure relief valve (not shown) that performs the analogous function for the PHTS and the other parts of the PHPB. Overpressure of the PHPB has the potential to lead to disruptions in the geometry of the reactor and core. Maintenance of these geometric features is required for public safety.

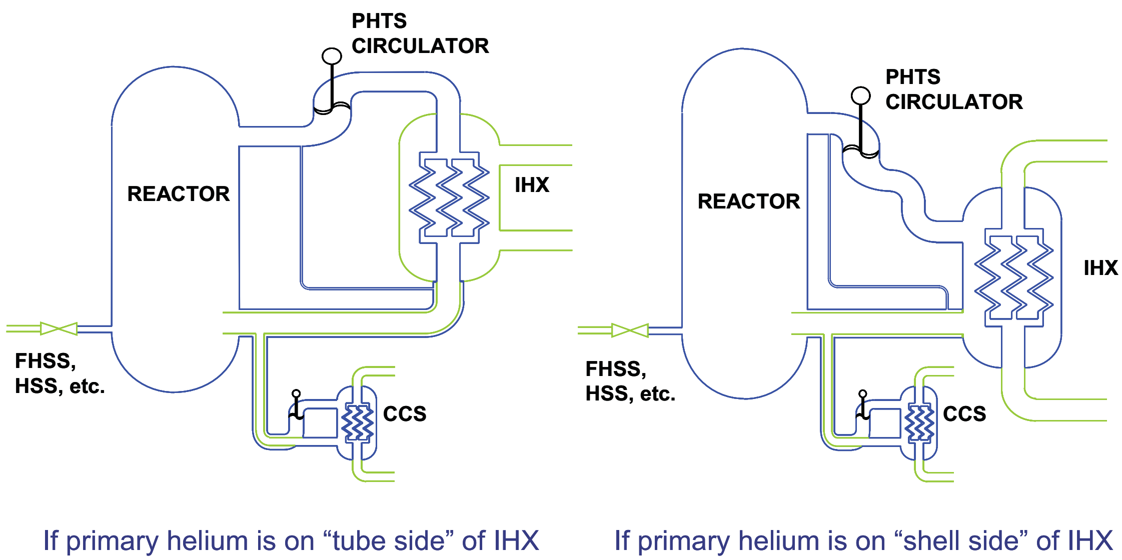


Figure 3-2 Primary Helium Pressure Boundary Extent

The Fuel Handling and Storage System (FHSS) and the Inventory Control Subsystem of the Helium Services System (HSS) interface with the PHTS. Isolation valves are included to disconnect these systems from the PHTS helium inventory, as is necessary for certain operational states and for maintenance of the HSS. The scope of this subtask concerns the primary and secondary loop configuration and, consequently, the discussion is limited to the potential need for fast-acting isolation valves that are within the HTS and not isolation valves at these system interfaces.

Within the PHTS, there is a self-actuated "flapper-type" check valve located upstream of the circulator, which is provided to limit backflow through the PHTS when the Core Conditioning System (CCS) is in operation. The PHTS check valve is not an isolation valve. As is the case with the PHTS, isolation valves are not needed within the SHTS to provide any functions during normal operation or during startup and shutdown.

In maintenance modes, where access to the PHTS and/or SHTS circulators is required, the PHTS and SHTS helium would be depressurized simultaneously to maintain a low pressure differential across the IHX; for the secondary circulators, the water/steam and sulfuric acid tertiary loops would additionally be depressurized and isolated. Sequences of steps similar to that for the circulators would apply for repair or replacement of the IHX, Steam Generator and Process Coupling Heat Exchanger(s) (PCHXs). Maintenance closure type isolation valves would be utilized after depressurization, when necessary, to isolate the reactor from the HTS. This is the approach presently taken in the DPP design.

Similarly, during other normal operation modes including starting up and shutting down, fast-acting isolation valves are not needed in either the PHTS or the SHTS to meet functional requirements.

3.2.2 Need for Isolation Valves in Response to Off-normal Events

The top level requirements summarized in Section 2 of the PCDR lead to design selections through a structured design process that first considers design selections supporting functions and requirements during all the modes and operating states of normal operation. Next, functions and requirements of off-normal events that challenge plant investment protection are addressed and, finally, those associated with off-normal events that challenge assurance of public safety are considered. This sequence avoids the inclusion of safety-dedicated SSCs that duplicate functions already required for normal operation and/or investment protection. As part of this examination of the need for fast-acting isolation valves, off-normal challenges to plant investment protection and public safety are discussed in the next subsection. Since fast-acting isolation valves are utilized in the design and licensing of LWRs to mitigate off-normal events involving loss of primary coolant, the licensing implications associated with the use of isolation valves in the PBMR NGNP are then discussed.

3.2.2.1 Challenges to Investment Protection and Public Safety

Requirements for investment protection center upon protecting the design features and associated structures, systems, and components (SSCs) that perform normal operation functions during off-normal operation to avoid excessive downtime and/or SSC repair and replacement. Requirements to assure of public safety focus on off-normal events that lead to off-site radionuclide release. In considering fast-acting isolation valves for the latter, four categories of off-normal events are addressed: 1) leaks in the PHPB including within the PHTS; 2) leaks in the SHTS helium boundary; 3) leaks between the PHTS and the SHTS, namely within the Intermediate Heat Exchanger (IHX); and 4) leaks within the PCHX or the PCS steam generator.

The NHSS and HTS are designed to meet investment protection and safety requirements for leaks from the PHPB. Since the PHPB is completely contained within the Nuclear Heat Supply Building (NHSB), leaks (other than in the PHTS IHX) depressurize helium into the citadel/NHSB which is designed to accommodate the pressure transient without compromising either the relative configuration of the Reactor Unit and the Reactor Cavity Cooling System (RCCS) or the core geometry, both of which are required to assure safety. To provide additional margin to requirements, leaks in some portions of the FHSS and HSS may be isolated by operator action, depending on leak location, to mitigate the loss of helium, to decrease the radionuclide cleanup time and/or to minimize the off-site release consequences.

Similarly, the NSSS and HTS are designed to meet investment protection and safety requirements for leaks from the SHTS. Leaks in portions of the SHTS can depressurize helium into the NHSB, including the citadel, which provides structural integrity around the Reactor Unit and RCCS as it does for the PHPB depressurization.

The Intermediate Heat Exchanger (IHX) is part of the PHPB and transfers heat from the Primary Heat Transport System (PHTS) to the Secondary Heat Transport System (SHTS). The IHX is designed to withstand full SHTS helium depressurization at temperature without failure propagating to the PHTS. In the reference PCDR design, the PHTS helium pressure is maintained at a slightly elevated pressure relative to the SHTS. This allows rapid identification of even small leaks across the IHX via the presence of radionuclides in the SHTS. When leaks are detected that exceed an acceptable level, the plant would be shut down for maintenance. Since significant leaks from the SHTS to the environment would be low-probability events, the presence of limited quantities of radionuclides in the SHTS for short periods of time would not, in and of itself, lead to a requirement for isolation valves. Note that both the PHTS and the SHTS have helium purification systems to assure that the normally circulating radionuclide inventory is acceptably low.

Alternatively, as being explored in this present study, the SHTS helium pressure may be maintained above the PHTS pressure. Small leaks in the IHX would then flow inward from the SHTS to the PHTS. As with the PCDR baseline, both the PHTS and the SHTS have helium purification systems to assure that the normally circulating radionuclide inventory is acceptably low. The acceptable level is much lower on the SHTS side. As noted in Section 1.2, the tradeoff with respect to the SHTS to PHTS bias option is that small IHX leaks are not likely to be detectable during operation, until they reach the level at which the SHTS to PHTS leak rate exceeds the normal PHTS outward leak rate, requiring helium extraction from the PHTS (as opposed to the normal replenishment). As with the reference PCDR design, the probability of coincident IHX and SHTS pressure boundary failure is extremely low, and ingress from the cleaner SHTS would not lead to any need for isolation valves. The recovery action for an IHX leak is to shut down the reactor and depressurize the PHTS and the SHTS helium together to keep the differential pressure across the IHX low. Maintenance valves similar to those selected for planned maintenance of the DPP would be employed to isolate the reactor for IHX repair and/or replacement.

Leaks in the PCHX are from the SHTS to the tertiary process loop, which has isolation valves. Leaks in the Steam Generator are into the SHTS from the Power Conversion System (PCS) water/steam inventory. The PCS has isolation valves and a steam generator dump system, and the IHX and the SHTS pressure relief valves will be designed to respond to in-leakage of an isolated steam generator if there is no dump of the inventory.

3.2.2.2 Licensing Implications

The NRC licensing perspective is heavily influenced by the over one hundred Light Water Reactors (LWRs) licensed and operating in the U. S. today. LWRs require that the primary coolant inventory be continuously maintained to adequately cool the reactor core and to meet investment protection and safety requirements. The loss of primary coolant boundary integrity leads to a loss of coolant and consequent loss of fuel integrity. For this reason, LWR primary coolant vessels and piping of related systems relied upon during DBAs are classified as safety-related up to an isolation valve, to assure high reliability in the maintaining of coolant inventory. The isolation valves in these systems must be fast-acting, as the power densities are relatively high and the thermal margins of the metallic fuel relatively low. These isolation valves are also utilized to avoid a radionuclide release pathway via containment building bypass. In addition, the design of LWR water systems take advantage of differing sections of the ASME Code, and some isolation valves are required to provide interfaces between ASME Code boundaries.

The PBMR modular HTGR, in contrast to an LWR, is designed to be cooled with or without full normal primary coolant (helium) inventory. In the PBMR, integrity of fuel is decoupled from integrity of the helium pressure boundary. Both active forced cooling and passive natural convection/conduction/radiation cooling do not require a full helium inventory. The low power density and large thermal margins allow for the passive removal of heat.

In a Modular HTGR, the helium pressure boundary vessels and piping that are relied-upon during DBAs are classified as safety-related. However, their safety function is not to keep the core covered, but rather to assure that core geometry is maintained and that the potential for chemical attack is controlled. Neither function is needed for small leaks, nor needs be met with fast acting isolation features. Primary radionuclide retention in the PBMR is within the coated fuel particles. Further retention is provided by the combination of the core, the PHPB and the NHSB. For this concentric barrier arrangement, isolation is not needed to avoid a bypass.

The PBMR safety design approach completely changes the paradigm through which one views the need for fast-acting isolation valves. Given this fact, the NGNP licensing approach will need to communicate these differences in safety fundamentals that are in contrast to those historically accepted for LWRs.

3.2.3 Prior HTGR Isolation Valve Technology Status

While the conclusion in the preceding sections is that the NGNP does not require in-line isolation valves in the helium circuits of the Heat Transport System, the work plan for this special study includes addressing the technology that might be applied to helium isolation valves, particularly technology from prior HTGR reactors and programs. Following are summaries of three options and assessment of their present state-of-the-art and technology development requirements.

3.2.3.1 German HTR Program, KVK Test

In the 1980s as part of the work in Germany on HTR development (PNP-Project) for process heat applications, a high temperature helium valve was designed and tested. The valve concept is a pneumatically actuated axial plug for location in the primary coolant circuit at the reactor vessel boundary (Ref. 3-1).

A scale illustration of the valve as-designed is shown in the upper portion of Figure 3-3. The valve sealing surface is at the circle indicated at a diameter of 700 mm. Two different sealing surfaces were developed and tested at Klinger Engineering (Vienna) and HRB Jülich: a chromium carbide and silver seat combination and an Alloy 800H and coated ZrC combination. The latter seems to have been the design selection. A full scale valve with connections to smaller scale piping was built and tested, and the test article is shown in the lower portion of Figure 3-3. The actuator was designed and separately tested by KWU.

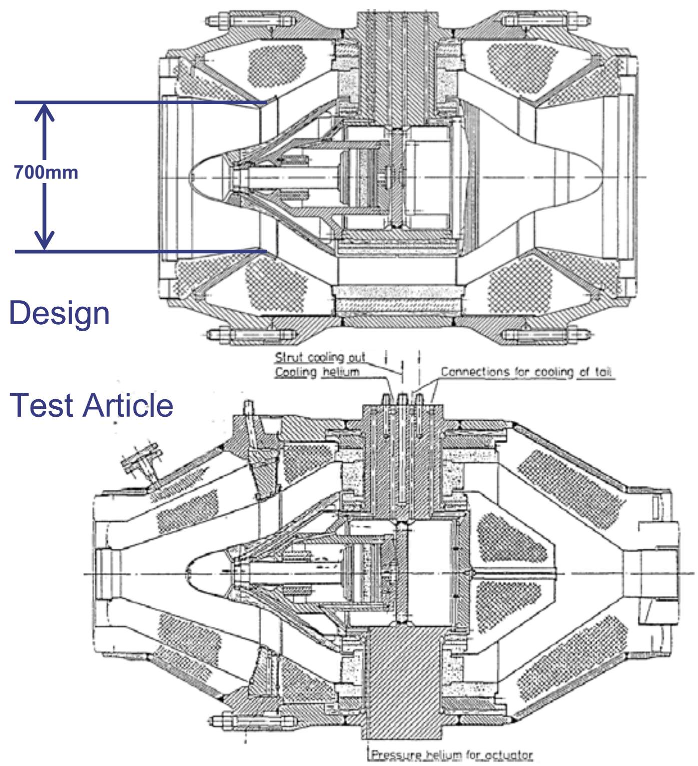


Figure 3-3 Designs of Valve and Test Article

Final testing was done in the KVK (Komponentenversuchskreislauf - Component Test Facility) at INTERATOM GmbH (Ref. 3-2). It is not clear whether the entire valve was tested at once or in separate leak and actuation time tests. Test results were that the valve had a leak rate of 10^{-1} scc/s at 42 bar pressure differential, and its actuation time was 300 ms. Figure 3-4 shows the photographs of components and test arrangements.

The German valve design was considered complete, with final engineering design verification testing partially completed at the end of the program in the mid-1980s. The valve design and testing were for an HTGR with 45 bar helium pressure, while the pressure for the preconceptual NGNP is 90 bar. Therefore, a modified design would be required for NGNP, should the requirement for such a valve arise.

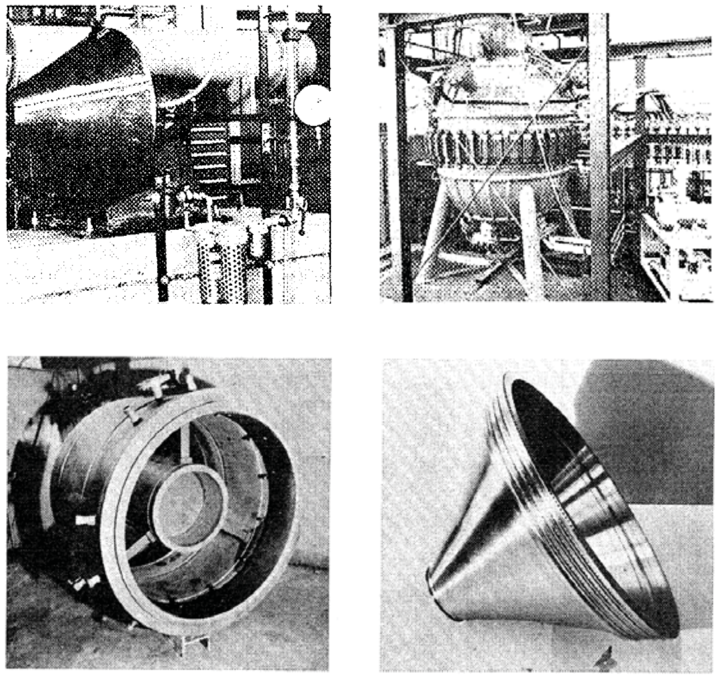


Figure 3-4 Components Tested and Test Assembly

It appears that this valve design is feasible to apply today, but because of the time elapsed since the work was done, the development would have to be repeated, and so this valve is not considered to be state-of-the-art.

3.2.3.2 Japan Atomic Energy Research Institute High-Temperature Isolation Valve

A High-Temperature Isolation Valve (HTIV) has been designed, as part of the Hydrogen Program of the Japan Atomic Energy Agency (JAEA). An example has been built and tested in ½ scale at 900°C. The design appears to be an angled globe valve with electrical or manual actuation, and this is shown in Figure 3-5. The valve seat material is Stellite.

From the description and partial test results (Refs. 3-3 & 3-4) the valve leakage was approximately 1.5×10^{-3} scc/s at 200°C and 5×10^{-3} scc/s at 900°C, whereas the target leak rate was 4.4 scc/s. Actuator testing was not reported. Figure 3-6 shows the valve test article.

This valve is sized for application to a secondary heat transport circuit for hydrogen production with the High Temperature Test Reactor (HTTR), which has a thermal power rating of 30 MWt and a primary coolant pressure of 40 bar. The PBMR NGNP would have a higher power rating and, consequently, a larger diameter piping. Also, the PBMR NGNP would have a higher coolant pressure and, therefore, more stringent pressure retaining duty. In summary, the HTTR valve, as developed, would not meet the requirements of the PBMR NGNP.

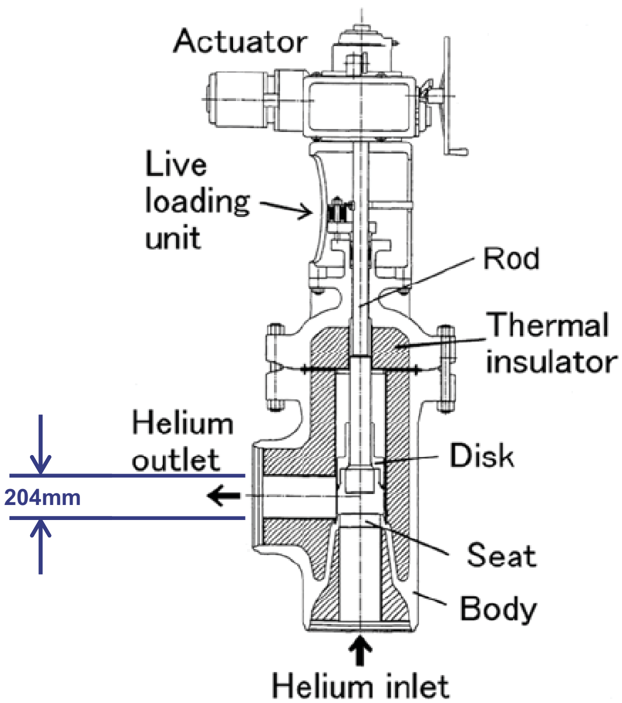


Figure 3-5 Diagram of HTIV

Figure 3-6 HTIV Test Article

Tests results are positive to date, and the technology utilized can be considered state-of-the-art. There would be further development and additional testing required to apply this valve to the SHTS piping of the NGNP. Compared to the German design of an in-line plug valve, there would be some concern about the pressure loss resulting from inclusion of such an angle valve in either the primary of secondary NGNP circuits.

3.2.3.3 Low Pressure Differential Gate Valve

The PBMR development program has considered a low-pressure differential gate valve as a possible maintenance closure. This valve concept could be applied to the NGNP for either a similar maintenance function or for use in response to certain depressurization events. (Although the PBMR NGNP fuel design is such that delayed release of fission products from the fuel particles during design basis events is to be well within the limiting offsite (EAB) doses calculated for corresponding frequencies, a low-pressure differential isolation valve might be considered for actuation several hours after the start of a depressurization event in order to re-close the PHPB.)

A typical concept for such a low pressure differential gate valve, housed inside a dedicated pressure vessel, is shown in Figure 3-7. Compared to the plug-type valves described in the preceding two sections, which seal at a seat into which the moving element of the valve is driven, gate valves seal along the surface of a moving element – a plate or disk. If the moving element is like a blade, it is referred to as a knife valve. If the plate or disk has a blank portion and a portion with a hole that either blanks off the pipe or allows a full flow passage of fluid through the pipe, it is referred to as a spectacle valve. These are specifically not wedge-type valves in which the closing action also includes a toggle or other mechanism to force the moving element onto the seals. Rather, the action is sliding against the seal seat. More specifically, in this design, the seals move away when the disc is inserted and then return to seal against the disc when it is in place. Knife gate valves are used for isolation in viscous fluids and flowing slurry. Spectacle valves are used in duct flow, such as of powders or flue gas. The sealing surfaces of such gate valves generally cannot withstand high differential pressure, because the moving element distorts under pressure and the seal is subject to deformation and leakage. There is also the design option to seal against pressure directed one way or both ways.

The valve comprises a housing and a lower circular body containing the sealing mechanism (see Figure 3-7). The upper section of the housing is provided for the stowage of the disc when the valve is open. The circular body comprises three bellows and a retractable ring, shown in Figure 3-8. Movement of the ring, which opens the path for insertion of the disc, is accomplished by inflating and deflating the void between two bellows through a pressurization and evacuation line in conjunction with the inherent spring force of the bellows. Creating a vacuum in the bellows retracts the ring and opens the sealing face for insertion of the disc. When the vacuum is released, spring force in the bellows moves the retractable ring to its closed or sealing position. Thereafter, continuous pressurization of the cavity between the two bellows is typically required to provide the necessary sealing force. A core advantage of this method is that the actuator can be significantly smaller than in other designs as it merely has to overcome friction in inserting the disc and is not required to overcome pressure forces in order to ensure seating or sealing of the disc.

This low pressure differential gate valve is a preliminary design for which the technology appears to be at hand, but which remains to be demonstrated.

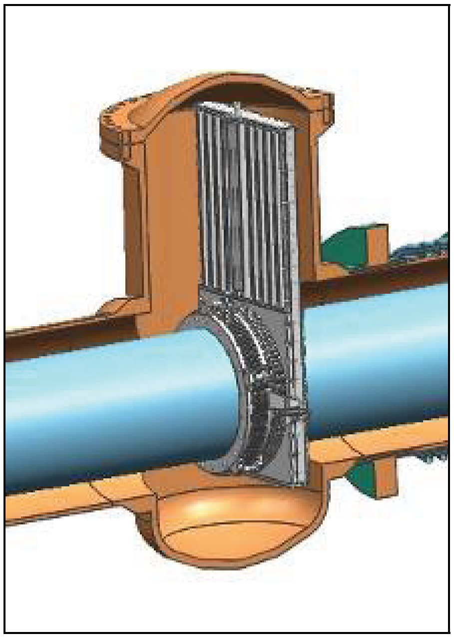


Figure 3-7 Valve Illustration

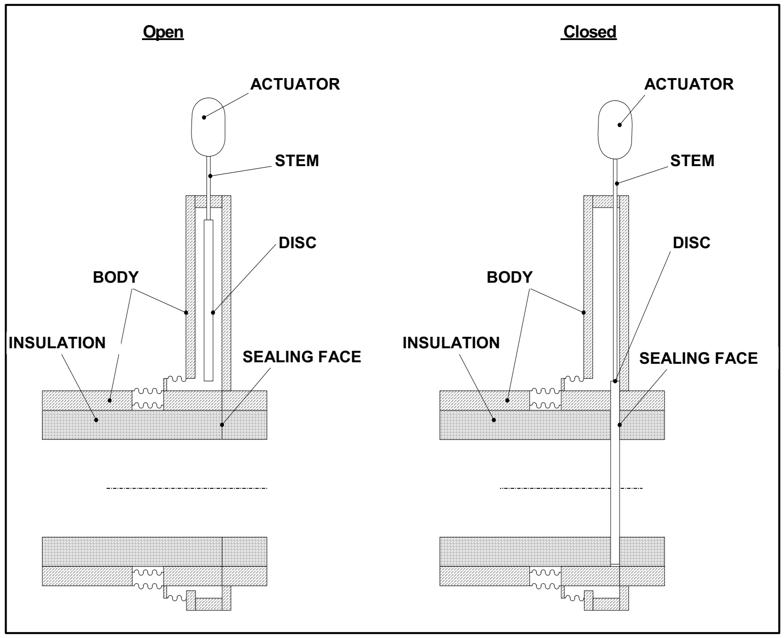


Figure 3-8 Valve Action

3.3 SG Assessment

This section evaluates the trade-offs between a single versus two-loop HTS from the Steam Generator (SG) perspective. A single-loop HTS will require a single 520 MWt SG, whereas, a two-loop HTS will require two smaller SGs (2x260 MWt). Figures depicting the architectures of the single and two-loop HTS configuration are shown later in Section 3.5. Note that, alternatively, the smaller 260 MWt SGs could be configured as parallel components within a single-loop HTS configuration.

The basic design of the evaluated SGs (Figure 3-2), is taken from the PBMR NGNP Preconceptual Design Report (Ref. 3-5 and 3-6). The design is based on the MHTGR-SC SG, which is described in Reference 3-7. The SG is a counter-flow, shell-and-tube, once-through non-reheat heat exchanger. In operation, helium flows downward across the helical tube bundles on the shell side of the SG. Cooled helium flows out of the SG tube bundle and upward through an annulus created by the SG outer shroud and the Steam Generator vessel I.D. On the tube side, feedwater is introduced at the bottom of the unit with superheated steam exiting from the top.

The present evaluation of the SG considers the following elements:

- Manufacturability
- Development Needs

- Economics
- Risk
- Schedule
- Operations
- Maintenance

This section is a Westinghouse Team summary of an evaluation completed by Doosan Heavy Industries and Construction (DOOSAN) (Ref. 3-8). DOOSAN has design experience with helical tube type Steam Generators and has been a manufacturer of PWR U-Tube Steam Generators since 1980.

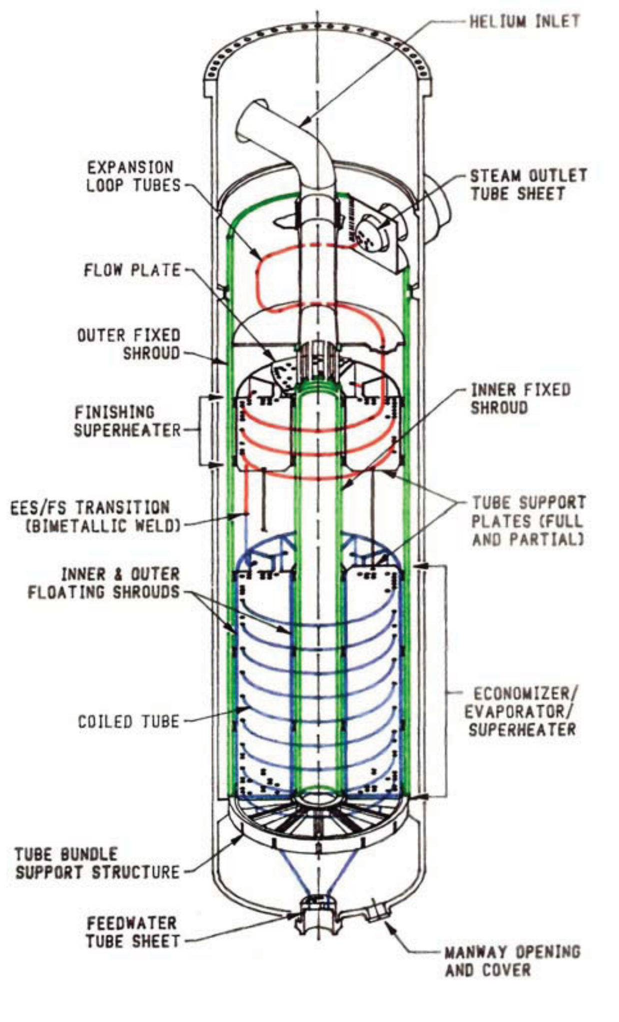


Figure 3-9 Helical Steam Generator

3.3.1 Manufacturability

The main manufacturing trade-offs are listed below (see Reference 3-8 for more details):

Shell Assembly: There are no material, fabrication or examination constraints for either a 520 MWt SG or 260 MWt SG because the shell size is within the current SG manufacturing capacity and capability.

Tubesheet: If a spherical tubesheet design is adopted, the 520 MWt SG is expected to be more complicated to fabricate due to drilling and arraying of tubes radially, tube-to-tubesheet welding on the spherical surface, and additional bending at the outside/inside surface of tubesheet. DOOSAN believes that this spherical shaped superheater tubesheet design can be changed to a flat-type tubesheet design, because large sized SB-564 Alloy UNS N08810 forgings can be manufactured. If the design is changed to flat tubesheet design, which will eliminate the disadvantage, there will be no difference in procuring a tubesheet for either size of SG.

Helical Tube Bundle: The 520 MWt SG and 260 MWt SG have 34 and 23 tube columns, respectively. In order to make pre-coiled tubes, development and fabrication of special tube coiling equipment will be needed, as will mandrels for each column of the tube bundle. Coiling equipment should be controlled by a Programmable Logic Controller that sets the coiling and transfer speeds of tubes. The helical angle of the tubes will be set by controlling the rotating speed of the mandrel about which a tube is wound and the transfer speed of the tube. When coiling tubes, the spring-back phenomenon should be considered to decide the diameter of the mandrel and also how much tension should be applied to tubes to minimize the spring-back. These must be verified through qualification or mockups. The 520 MWt SG will have a larger coil diameter. Special equipment is needed to handle and install the tubes for both sizes; however, a larger coil diameter is more difficult with respect to tube handling, because it is more flexible. Also, the lead in/ lead out and expansion region of the 520 MWt SG is more complex. Overall, manufacturing of the coiled tube bundle for the 520 MWt SG is more difficult than for the 260 MWt SG.

Shroud Assembly: Based on available information, there is no significant difference in making the shroud assembly for the large and smaller SG.

In summary, fabrication of the 520 MWt SG is more challenging than the 260 MWt SG, mainly due to the larger-sized helical tube bundle. However, both SG sizes can be manufactured considering current manufacturing capabilities.

3.3.2 Differences in Development Needs

The 520 MWt SG has a larger spiral coiling diameter and more tube columns, which consequently require the development of larger coiling equipment. Tube coiling equipment and tube installation equipment will be required to make pre-coiled tubes and to install the tubes within the tube holes in the tube support plates by rotating the tube itself. Coiling equipment could be similar to a lathe, which is composed of head stock, tail stock, carriage, bed, etc. The 520 MWt SG has a more complicated lead-in/ lead-out configuration, which needs more consideration in tube array design.

3.3.3 Economics

The estimated manufacturing cost of two combined 260 MWt SGs is expected to be 30% higher than for a single 520 MWt (including material, labor and expenses). Details of the comparison are shown in Table 3.2.3. The transport cost to a US port is a little higher for the 1x520 MWt case. The additional costs for transport from the U.S. port to the plant site are not included in the present assessment.

Table 3-2 Relative Economic Comparison

Steam Generator	1x520 MWt 6m x 20 m, 500 ton	2x260 MWt 4.3m x 20 m, 330 ton
Design Cost	1.00	1.00
Manufacturing Cost	1.00	1.29
• Material Cost (80%)	1.00	1.16
• Labor Cost (13%)	1.00	1.70
• Expenses Cost (7%)	1.00	2.00
Transportation Cost[1]	~$800,000	~$750,000
[1] CIF New Orleans Port 45-50 days duration		

3.3.4 Risk Considerations

Fabrication of the helical tube bundle for a 520 MWt SG is more complicated than that for a 260 MWt SG, due to the larger number of tube columns, larger size of the coiling diameter, heavy duty coiling equipment (including mandrels) to make and install the pre-coiled tubes, etc. A single 520 MWt SG is, hence, anticipated to have increased risk in terms of manufacturability, mainly because of the larger size of the helical tube bundle, as described above. However, the risk of manufacturing both a single 520 MWt SG and two 260 MWt SGs is within acceptable levels, since both sized SGs are within current manufacturing capabilities.

Transport of the SG presents a potential risk that the larger SG would exceed transport limits and require on-side assembly. However; an initial assessment of the 520 MWt SG, documented in Section 8 of the PCDR (based on an estimated size of 18.3m long, 5.2m diameter, 600t), suggests that the SG is transportable to the INL site via a carefully planned and executed transportation scheme (Ref. 3-5)

3.3.5 Schedule

No significant difference is foreseen in schedule implications for the two SG sizes. The advantage of selecting a single SG instead of two SGs will be offset by the disadvantage of making the bigger sized SG considering the following:

- A single larger sized, 520 MWt SG will take more time to fabricate than a single smaller sized 260 MWt SG (time difference will be within few months).
- Two smaller sized 260 MWt SGs can be fabricated in parallel with some time interval between. The time interval is estimated to be similar to the time saved due to making smaller sized SGs compared to the larger sized SG.
- The time interval in parallel fabrication is caused by limited resources, such as man power, drilling machine, coiling machine, etc.

3.3.6 Operations

The main operational trade-offs are listed below (see Reference 3-8 for more details):

Uniformity of Once-Through Boiling of All Tubes: To achieve uniform once-through boiling of all tubes, each tube has to have a uniform length and configuration. But each tube must have a slightly different helix angle to create a uniform radial pitch, due to the different tube quantity and helix diameter per each tube column. To compensate for this difference, a customized tube orifice can be adopted. Generally, this fluctuation is slightly bigger in the smaller diameter tube column, but there is no significant difference.

Uniformity of Helium Flow Distribution to All Tubes: The larger cross section area of a 520 MWt SG tube bundle may cause more local flow concentration, compared to the smaller sized 260 MWt SG. It is, therefore, reasonable that the smaller steam generator is less susceptible to flow maldistribution. However, it is believed that appropriate flow distribution devices could be used to achieve comparable flow distributions within in the larger SG.

Steady State Operation with BMW Conditions: The flow field in the BMW would be affected by the inlet condition to the BMW region. The larger sized 520 MWt SG is more susceptible to local flow concentrations. Thus, the smaller sized 260 MWt SG is advantageous.

Boiling Stability over a Range of Power Levels: From the standpoint of two-phase flow resistance, both steam generators have very similar characteristics because the average tube length and orifice design concept would be similarly adopted. So, it is reasonable that both steam generators would have the same benefit with respect to flow stability of tube-side boiling.

FOAK Instrumentation to Allow Tuning of Operation: Thermocouples can be inserted through holes into the horizontal support plate, which is installed in the BMW region, to contact surface of tube. With four shell inspection ports and three thermocouples per port, a total of twelve tube temperatures can be measured. There is no considerable difference between the 260 MWt SG and 520 MWt SG with respect to installing thermocouples, assuming that the horizontal support plate can be installed. However, the feasibility of installing this kind of horizontal support plate should be further considered.

Overall, the differences between the two SG sizes appear minor, except for the shell-side flow characteristics. The 260 MWt SG can expect a better uniformity of helium flow distribution, without incorporating additional flow distribution devices.

3.3.7 Maintenance

Key maintenance trade-offs are listed below (see Reference 3-8 for more details):

Access to Individual Tubes for Inspection, Plugging: The 520 MWt SG is preferable, because of greater work space. But inspection and plugging of individual tubes is also possible for the 260 MWt SG.

Access to the Helium Side for Remote Visual Inspection: No difference is expected between a single 520 MWt SG and two 260 MWt SGs. Manway and work space in the shell would be provided to access the helium side. Considering the overall length and shell ID of both designs, the manway can be provided for both designs. Remote accessibility to the helium side along the tube length depends on the lead-in/lead-out region tube configuration. An inspection port in the BMW region and horizontal tube support plate is suggested for remote visual inspection of the transition region.

Handhole or Larger Access to Critical Items Such as the BMW: The 260 MWt SG is preferable in terms of accessibility to BMW, due to the distance between the handhole and the innermost BMW. There are no differences in making handholes for both designs. But for accessibility, a smaller diameter tube bundle is preferable to access each BMW. If the tube support plate for installing thermocouples is adopted, the tube support plate can be used for this purpose also.

In summary, ease of maintenance is viewed to be similar for both options.

3.3.8 Summary of Tradeoffs

The evaluation indicates that a single 520 MWt SG design has increased challenge and risk with respect to manufacturing (consequently having more development needs); however the increased manufacturing difficulty is still within current manufacturing capacity/technology. This is mainly due to the larger number of tube columns and the larger diameter of the tube bundle. However, its overall cost is estimated to be 30% lower than two 260 MWt SGs. Other factors indicate no significant differences. See Table 3-3 for further summary.

Table 3-3 Steam Generator Trade-Off Summary

	Steam Generator	
Number of Loops	**1 A single 520 MWt SG**	**2 Two 260 MWt SGs**
Manufacturing	Acceptable	Better (Tubes)
Operability		Slightly Better
Maintenance	Similar	Similar
Development Needs	More	
Capital Cost	Better (~30% less)	
Risk	Acceptable	Slightly Lower (Tubes)
Project Schedule	Similar	Similar

3.3.9 Conclusion

Since both designs can be manufactured with current technology and are viewed to have acceptable risk, it is recommended that a single 520 MWt design be pursued due to its lower cost. This recommendation should be further evaluated if transport limitations to the U.S. site are found to require on-site assembly of one, but not both SG sizes.

3.4 Options for Coupling of the IHX to the PHTS and SHTS

In the overall development of the HTS, one key decision that must be made is whether to couple the primary heat transport system (PHTS) to the shell side or core side of the IHX. In this context, the "core side" of the IHX is analogous to "tube side" of a conventional shell and tube heat exchanger. Selection of the preferred (core or shell) side for coupling the IHX to the PHTS involves a number of tradeoffs that are summarized in Table 3-4 and discussed within this section. After review of the background and assumptions in Section 3.4.1, the individual tradeoffs are discussed in detail in Section 3.4.2. Conclusions of the evaluation are given in Section 3.4.3. Color coding employed in Table 3-4 is intended to highlight relative differences among options, not to indicate whether a particular option is acceptable or not acceptable.

Table 3-4 Tradeoffs Related to Core-Side vs. Shell-Side IHX Coupling

Objectives:

1. **Provide a qualitative comparison of alternatives for coupling the IHX to the PHTS and SHTS**
2. **Include consideration of Higher Pressure in the PHTS vs. SHTS**

Assumptions

1. PHTS and SHTS are pressurized helium closed loops.
2. The reference NGNP IHX comprises two IHX sections in two separate vessels and is generally consistent with the layout depicted for Concept C in Section 1.4.2 of the present study. For cases in which the shell side of the IHX is coupled to the PHTS, the PHTS and SHTS flows would be reversed relative to the description in Section 1.4.2.
3. The IHX core may be of the Unit Cell (plate-fin) or PCHE (microchannel plate) type. Differences will be noted, where relevant.
4. The PHTS and SHTS are nominally pressure balanced during all modes and states and for events, except "Loss of Secondary Pressure" which is assumed to be a Design Basis Event (DBE) for the purposes of this study.
5. The SHTS will be designed to ASME Section VIII.
6. SHTS piping can be designed with passive insulation (instead of active cooling).
7. Tubes connecting individual IHX cores to top/bottom ducts can be plugged.
8. Leaks are not due to common-mode failures.
9. For the option in which the PHTS is coupled to the core side (core interior) of the IHX, the arrangement is assumed to be as shown for HTS Option P1 (see Fig. 1). For the options in which the PHTS is coupled to the shell side of the IHX, the arrangements are assumed to be as shown for HTS Option S2 (see Fig. 2) or S3 (see Fig. 3).

Figure 1 - HTS Option P1

Figure 2 - HTS Option S2

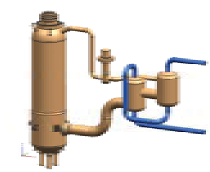


Figure 3 - HTS Option S3

Color Key: Green = Relative Advantage, Red = Relative Disadvantage, Black = Neutral/No Difference

Note: As used in this table, the color coding is intended to highlight relative differences among options, not to indicate whether a particular option or feature is acceptable or unacceptable.

Table 3-4 Tradeoffs Related to Core-Side vs. Shell-Side IHX Coupling (cont'd)

Consideration	Core-Side Coupling (P1)	Shell-Side Coupling (S2)	Shell-Side Coupling (S3)
Design & Development			
Vessel Supports	RPV position fixed, IHX A Vessel fixed laterally, vertically, but allowed to rotate on trunnion; IHX B Vessel fixed laterally, allowed to grow vertically and rotate with IHX A; flexibility built into Reactor Outlet and Inlet Pipes.	RPV and Circulator Vessel fixed, IHX Vessels allowed to move on sliding supports along axis of reactor outlet pipe; constrained vertically and laterally perpendicular to pipe axis. Flexible piping to and from Circulator. Concept similar to LWR supports.	RPV, IHX A, IHX B and Circulator Vessels fixed. Flexibility built into Reactor Outlet and Inlet Pipes.
PHTS Circulator	Mounted on top of IHX B. Alternative is to locate in vessel in return piping between IHX and RPV	Circulator located in vessel in return piping between IHX and RPV.	Circulator located in vessel in return piping between IHX and RPV.
Cooled Hot Gas Ducts/Pipes			
- Pipe Lengths	Longer pipe required for bend, flexibility	Shortest lengths	Longer pipe required for bend, flexibility
- Pipe Complexity	Bend in RPV to IHX A pipe	Straight pipes only (Note: May not be acceptable - see RIM)	Two bends in RPV to IHX A pipe
Cold-Leg Piping			
- Pipe Lengths	Shorter due to 1 run, close IHX B proximity to RPV	Longer due to 2 runs, greater distance to IHX B	Longer due to 2 runs
- Pipe Complexity	No significant differences	No significant differences	No significant differences
IHX			
- Cores	No significant differences	No significant differences	No significant differences
- Manifolds/Internal Piping	Operate at ~950C	Operate at ~900C	Operate at ~900C
- Shell-Side Internal Ducts, Baffling	Operate at ~900C, flow from outside to center.	Operate at ~950C, flow from center to outside.	Operate at ~950C, flow from center to outside.
- Pressure Biasing: Plate-Fin			
. SHTS > PHTS	Normal operation: 100kPa external pressure LOSP: 9MPa internal pressure) (LOSP = Loss of Secondary Pressure)	Normal operation: 100kPa internal pressure LOSP: 9MPa external pressure)	Normal operation: 100kPa internal pressure LOSP: 9MPa external pressure)
. PHTS > SHTS	Normal operation: 100kPa internal pressure LOSP: 9MPa internal pressure)	Normal operation: 100kPa external pressure LOSP: 9MPa external pressure)	Normal operation: 100kPa external pressure LOSP: 9MPa external pressure)
- Pressure Biasing: PCHE	No significant differences	No significant differences	No significant differences
IHX Vessel			
- Insulation/Cooling	SHTS cooling gas available at ~287C Separate active cooling source required for vessels (SHTS) and RPV to IHX hot duct (PHTS) or hot duct becomes PHTS/SHTS boundary.	PHTS cooling gas available at ~350C Same cooling gas can be used for vessels and RPV to IHX hot duct.	PHTS cooling gas available at ~350C Same cooling gas can be used for vessels and RPV to IHX hot duct.

Table 3-4 Tradeoffs Related to Core-Side vs. Shell-Side IHX Coupling (cont'd)

Consideration	Core-Side Coupling (P1)	Shell-Side Coupling (S2)	Shell-Side Coupling (S3)
Manufacturing and Construction			
IHXs, Vessels and Piping	No significant differences	No significant differences	
Operation and Maintenance (O&M)			
Performance	No significant differences	No significant differences	
Reliability and Integrity Management (RIM)			
- Leak Detection - Plant in Operation			
. SHTS Pressure > PHTS	Small leaks would likely not be detected. Indications of larger leaks would be inability to maintain bias dP and/or excessive injection of makeup helium into SHTS and withdrawal from PHTS. Since no contamination, larger leaks may be allowed.		
. PHTS Pressure > SHTS	Small leaks would be detected by presence of small amounts of radionuclides in SHTS.		
- In-Service Inspection			
. Central Ducts and Manifolds	Access for NDE conceptually available from contaminated PHTS side. Would require isolation of reactor (e.g., maintenance disks as envisioned for DPP) and opening of PHTS pressure boundary (PB). Access to top and bottom of IHX sections would involve removal of PHTS pipe sections above, below and between the IHX sections and/or removal of one or both of the IHXs. Note that the pipe to IHX A and the pipe between IHX A and B are actively cooled double-walled sections.	Access for NDE is available from uncontaminated SHTS side. Requires removal of single wall pipe sections from above and below. No requirement to open PHTS PB or to move IHX. Neutron "shine" via outlet plenum to shell side of IHX through straight pipe is unacceptable due to potential for activation of IHX A internal components.	Access for NDE is available from uncontaminated SHTS side. Requires removal of single wall pipe sections from above and below. No requirement to open PHTS PB or to move IHX.
. IHX Cores	NDE methods, such as UT, MT, RT do not appear to be practical. One option is to pressure test individual modules. Access via manifolds is as described above. PHTS contamination a potentially significant factor.	NDE methods, such as UT, MT, RT do not appear to be practical. One option is to pressure test individual modules. Access via manifolds is as described above. PHTS contamination not a significant factor, but activation may be.	NDE methods, such as UT, MT, RT do not appear to be practical. One option is to pressure test individual modules. Access via manifolds is as described above. PHTS contamination not a significant factor.
- Leak Location and Isolation	Individual modules may be tested for leakage and isolated by plugging via access to IHX central duct. This access is obtained as described above.		

Table 3-4 Tradeoffs Related to Core-Side vs. Shell-Side IHX Coupling (cont'd)

Consideration	Core-Side Coupling (P1)	Shell-Side Coupling (S2)	Shell-Side Coupling (S3)
Operation and Maintenance (O&M) (cont'd)			
- IHX Replacement			
. IHX A	Requires removal of IHX B or provisions for lateral displacement of IHX A before removal/replacement.	Direct access to IHX A for removal/replacement.	Direct access to IHX A for removal/replacement.
. IHX B	No significant differences	No significant differences	No significant differences
- Circulator Maintenance	Good access to circulator for maintenance. IHX maintenance requires circulator removal, if placed at the top of IHX B.	Good access to circulator for maintenance. IHX maintenance does not require circulator removal.	Good access to circulator for maintenance. IHX maintenance does not require circulator removal.
Investment Risk			
- Chemistry/Corrosion			
. Plate-fin	Internal core must be compatible with PHTS chemistry (more difficult to control). Importance related to fin condition during LOSP.	Internal core must be compatible with SHTS chemistry (less difficult to control). Fins loaded in compression during LOSP	Internal core must be compatible with SHTS chemistry (less difficult to control). Fins loaded in compression during LOSP
. PCHE	No significant differences	No significant differences	No significant differences
- Dust (blockage, erosion)	Dust more likely to enter IHX core passages.	Dust more likely to drop out, less likely to enter IHX core passages (To be confirmed).	Dust more likely to drop out, less likely to enter IHX core passages (To be confirmed).

Table 3-4 Tradeoffs Related to Core-Side vs. Shell-Side IHX Coupling (cont'd)

Consideration	Core-Side Coupling (P1)	Shell-Side Coupling (S2)	Shell-Side Coupling (S3)
Safety & Licensing			
ALARA			
- Neutron Activation	Bend in Reactor Outlet Pipe places IHX A out of reactor neutron path, thus minimizing potential for activiation	Straight Reactor Outlet Pipe places IHX A in line with outlet plenum of reactor. While well below the core, there is a likelihood that "shine" from reflected/scattered neutrons during operation will result in unacceptable activation of the IHX A internal components.	Bend in Reactor Outlet Pipe places IHX A out of reactor neutron path, thus minimizing potential for activiation
- Direction of Pressure Bias			
. SHTS Pressure > PHTS	IHX internal pressure boundary leaks during normal operation do not contaminate the SHTS		
. PHTS Pressure > SHTS	IHX internal pressure boundary leaks during normal operation imply contamination of the SHTS (levels, implications TBD)		
Loss of Secondary Pressure			
- Plate-fin	Internal pressurization of cores makes secondary failures more likely.	External pressurization of cores makes secondary failures less likely.	External pressurization of cores makes secondary failures less likely.
- PCHE	No significant differences	No significant differences	No significant differences
Project Life Cycle Cost			
Design & Development Costs	Maintenance design and qualification more challenging	Maintenance design and qualification less challenging	Maintenance design and qualification less challenging
Capital Costs	No significant differences	No significant differences	No significant differences
Project Schedule	No significant differences	No significant differences	No significant differences
Operating Costs	Maintenance costs would be higher for equilivent functions	Maintenance costs would be lower for equilivent functions	Maintenance costs would be lower for equilivent functions
Risk	Consequences of leaks, dust/erosion, LOSP would be more significant	Consequences of leaks, dust/erosion, LOSP would be less significant	Consequences of leaks, dust/erosion, LOSP would be less significant

3.4.1 Background and Assumptions

As part of the PBMR NGNP Preconceptual Design (Ref. 0), the reference HTS layout incorporates a printed circuit heat exchanger (PCHE) IHX. The shell side of the IHX is coupled to the PHTS and the core side to the SHTS. The PHTS and SHTS are essentially pressure balanced during all plant modes and states, with the exception of pressure testing and Design Basis Events (DBEs) involving the loss of primary or secondary pressure. In the PCDR design, pressure biasing is from the PHTS to the SHTS, which provides for the rapid identification of small leaks in the PHTS to SHTS interface via the detection of radionuclides in the SHTS. In the present evaluation, the PHTS layout that is analogous to the reference PCRD design is Option S2 (See Section 1.3).

In the present study, an alternative approach has been explored in which the core side of the IHX is coupled to the PHTS. The IHX considered in this study is of the plate-fin type. Pressure biasing is from the SHTS to the PHTS, which results in the cores being loaded in compression during normal operation. Small leaks in the PHTS to SHTS interface would not result in radionuclide contamination of the SHTS; however, it is unlikely that small leaks could be detected during operation. In the present study, the reference HTS layout representative of this configuration is Option P1 (See Section 1.3).

The overall objective of this section is to provide a qualitative comparison of alternatives for coupling the IHX to the PHTS and SHTS. Note from the above that two related design selections have a bearing on the IHX coupling decision process. These are the design of the IHX itself and the direction of pressure biasing between the PHTS and SHTS. Where these related design selections have a bearing on the coupling option decision process, their influences are noted in Table 3-4, and the accompanying discussion that follows.

The assumptions underlying the comparison that follows are summarized at the top of Table 3-4. It is assumed that both the PHTS and SHTS utilize helium as the working fluid and operate in an essentially pressure-balanced condition. Consistent with the results of Sections 1.1 and 1.6, options for the IHX are limited to the plate-fin and PCHE designs. Consistent with the reference PCRD design (Ref. 0), the IHX is assumed to be configured into high- and low-temperature sections, designated IHX-A and IHX-B, respectively. The HTS options upon which the comparisons are based are Option P1 for core-side coupling and Options S2 and S3 for shell-side coupling.

3.4.2 Comparison of the Options

Consistent with the evaluation in Section 3.5, the core- vs. tube-side PHTS coupling options are structured within five categories that are individually addressed within the following subsections.

3.4.2.1 Design and Development

The following differences have been identified that might influence the design and/or development of the HTS.

Vessel Supports

Differences in the vessel support systems result from the basic configuration of the IHX (Section 1.4.2) and the relative arrangements of IHX-A versus IHX-B. For core-side coupling, the primary helium enters and leaves the IHX sections at the top and bottom of the vessels. HTS configuration studies, documented in Section 1.3, have indicated that the preferred configuration for the core-side coupling option is a vertical in-line arrangement of IHX-B over IHX-A. This leads to a support arrangement in which both the reactor pressure vessel (RPV) and IHX-A are fixed in location, both vertically and laterally. IHX-A is allowed to rotate on trunnion. IHX-B is fixed laterally, but allowed to move vertically. Flexibility is provided in the reactor outlet pipe/hot duct to accommodate thermal expansion. The circulator is mounted at the top of IHX-B. A flexible cold-leg pipe returns the helium to the reactor. This concept is similar to that used for the PBMR DPP recuperator support. The key requirement is that the length and configuration of the reactor outlet pipe/hot duct be such that the required flexibility is obtained.

For shell-side coupling, the primary helium enters and leaves the IHX sections at the side of the vessels. This leads to a side-by-side arrangement of IHX-A and IHX-B, consistent with the reference PCRD design. The circulator is located in a separate vessel in the cold-leg pipe returning to the RPV. The support system envisioned for this option is based on standard light water reactor (LWR) designs in which the RPV is fixed and the IHX vessels are allowed to move on sliding supports along the axis of the reactor outlet pipe/hot duct. The circulator vessel is also fixed, with flexibility provided in the cold-leg piping.

While different, no compelling advantages or disadvantages are seen for these alternate support concepts.

PHTS Circulator

With core-side coupling, the circulator may be mounted at the top of IHX-B, as shown for Option P1 or placed in the cold-leg pipe. With shell-side coupling, the circulator is required to be located in the cold-leg pipe, returning to the RPV, requiring a separate vessel. Again, while Option P1 offers flexibility of circulator location, no compelling advantages or disadvantages are seen for these alternatives.

Actively Cooled Hot Gas Ducts (HGD) /Piping

The actively-cooled hot gas ducts/pipes in the PHTS are complex structures that result in both complexity and high cost. The minimal lengths and straight sections of the shell side coupling option are optimal in this respect. Option S3 has two HGD bends, while Option P1 has one HGD bend. However, for both options, the HGD is evaluated to be acceptable. Option S2 offers the shortest HGD; however, consequently results in a direct path of neutrons from the reactor outlet plenum to the IHX (see subsequent sections).

Cold-Leg Piping

Compared with the actively cooled hot gas ducts/piping, cold leg piping is relatively simple and inexpensive. An advantage accrues to the core-side coupling option, due to its shorter overall length.

IHX

Within the IHX, the principal differences between the core-side and shell-side coupling options are found in the internal flow paths. Note that the directions of the flow paths are reversed in going from the core-side to the shell-side option in order to provide the cooler temperatures at the walls of the IHX vessels. Taking the cores, manifolds/internal piping and shell-side baffling as a whole, there are offsetting advantages and disadvantages, with no significant resulting preference.

The PCHE is indifferent to the direction of pressure biasing and loss of secondary pressure (LOSP); however, these are potentially significant factors for the plate-fin design. The preferred loading direction for the plate-fin design is from the shell side. This results in compressive loading of the fins and brazed joints, which minimizes the likelihood of a PHTS to SHTS breach. Note that there are two categories of loads that are of interest for this comparison. The first is long-term normal operation at the nominal differential pressure load and at high temperature. The second is the loss-of-secondary-pressure (LOSP) design basis event, which involves a 9 MPa pressure difference over a relatively short period. Taken together, the optimum configuration for these events is that of the reference PCDR design, which has shell-side PHTS coupling and PHTS to SHTS pressure biasing. For the P1 configuration evaluated in this study (core-side coupling and SHTS to PHTS pressure biasing), the pressure differential is advantageous for normal operation, but not for the LOSP event. The reverse is true for the shell-side coupling options, S2 and S3. Scoping analyses addressing both normal operation and LOSP suggest that all of the coupling options may be acceptable; however, this needs further confirmation.

IHX Vessel

Due to the high temperatures within, the IHX-A vessel (assumed to be fabricated from SA-508/SA-533 low-alloy steel) will need to be actively cooled to limit the temperature of the pressure boundary material to 371°C. It is preferred to extract the cooling flow from the coolest part of the shell-side circuit. For the core-side coupling option, cooling gas is available at 287°C. For the shell-side coupling option, the coolest gas available is at 350°C. The implications of this difference (reduced margins and, potentially, a change in vessel material) will need to be further assessed. Note that, in any event, the PHTS pressure boundary piping enclosing the HGD from the RPV to the IHX vessel will be cooled with PHTS helium at 350°C.

3.4.2.2 Manufacturing and Construction

Considering the IHXs, vessels and associated piping, no significant differences were identified in the category of manufacturing and construction. Further consideration of the vessel arrangements, details of the respective support systems and associated building features might reveal advantages and/or disadvantages; however, these would not be expected to be compelling.

3.4.2.3 Operation and Maintenance

Three categories are assessed within the framework of operations and maintenance (O&M). These are performance, reliability and integrity management, and investment risk.

Performance

No significant performance differences were identified between the three coupling options.

Reliability and Integrity Management

In the category of reliability and integrity management (RIM), key differences were found in the ability to access the IHX internal manifolds that connect the central ducts to the heat transfer modules and, thereby, to locate and potentially isolate leaks that might occur in the PHTS to SHTS interface. The significance of this capability will depend on the likelihood of leaks and whether the leaks are random or from "common-mode" failures, in which case the entire IHX would need to be replaced.

When the plant is in operation, the detection of leaks in the PHTS to SHTS interface is principally influenced by the direction of pressure bias, which can be independent of which option is selected for IHX coupling (also see pressure bias trade-offs in Table 3-4 under the heading "Design & Development, IHX, Pressure Biasing" and accompanying discussion in Section 3.4.2.1). In the case of the reference PCDR design, in which the bias is from the PHTS to the SHTS, relatively small leaks would be detectable by the presence of radionuclides in the SHTS. This, of course, infers that the SHTS helium purification system must take the possibility of such leaks into account and there is a potential impact on availability in the event of small leaks that otherwise might be tolerable. With SHTS to PHTS pressure biasing, it is unlikely that small leaks would be detected. Larger leaks would be detected initially by either the inability to maintain the desired pressure bias or by excessive injection of SHTS makeup helium and/or excessive withdrawal of PHTS helium. A potential advantage of SHTS to PHTS pressure biasing is being able to operate with small leaks, since leaking of the SHTS helium into the PHTS would not result in contamination. The significance of the differences in detection capability and availability implications of contamination require further assessment.

A key difference in the core-side versus shell-side coupling options is found in the relative difficulty of assessing the condition of the IHX internal components during maintenance outages and responding to indications of PHTS to SHTS leaks.

A notable advantage of the IHX design developed in the course of this study is the ability to individually access the manifold pipes that connect the core-sides of the IHX heat transfer modules to the central inlet and outlet ducts. In concept, this feature is applicable to both the plate-fin and PCHE heat exchanger core designs.

With the shell-side coupling option, as configured in the Option S2 and S3 arrangements, independent access is available to the SHTS inlet and outlet ducts at the tops and bottoms of IHX-A and IHX-B by removing corresponding sections of the SHTS piping. There is no need to breach the PHTS pressure boundary, and access is from the uncontaminated side of the IHX. Once access is obtained, the central ducts and the individual pipes between the central ducts and the heat transfer modules are available for evaluation, using standard non-destructive examination (NDE) techniques, such as ultrasonic evaluation. At this time, there does not appear to be a practical NDE method for evaluating the condition of the heat transfer modules themselves, with one exception. That is, it would be potentially feasible to conduct a pressure test of individual modules, together with the pipes that connect them to the central ducts. If a leak were present and was detected during such examinations, the pipes leading to and from the individual modules may be plugged at their interfaces with the central ducts. This would avoid the need to remove and replace an IHX in the event of spurious links.

With the core-side coupling arrangement of Option P1, the access and maintenance options, described above, are conceptually feasible, but may be difficult to the point of being impractical. Access to the central inlet and outlet ducts requires opening of the PHTS circuit at the tops and bottoms of IHX-A and IHX-B. Before doing so, it would be necessary to insert maintenance plugs in the reactor outlet and inlet pipes, likely using techniques similar to those developed for the PBMR DPP. Removal of the PHTS piping at the bottom of IHX-A and top of IHX-B would be more complex, due to the double-wall/insulated construction of the actively cooled piping to IHX-A, plus PHTS radionuclide contamination. Removal of the actively-cooled straight pipe section between IHX-A and IHX-B appears conceptually more difficult, and may require movement or removal of IHX-B. Once access is obtained, inspection and/or maintenance operations must be undertaken under contaminated conditions.

Regarding IHX replacement, there would be no substantive difference between the coupling options for the replacement of the IHX-B. For the replacement of IHX-A (more likely to require replacement due to higher temperatures), the shell-side coupling option, S2, allows direct access for replacement, without disturbing IHX-B. Replacement of IHX-A with the core-side coupling option, P1, would require either the removal of IHX-B, or provisions for lateral displacement of IHX-A in conjunction with removal and replacement.

Both the core-side and shell-side coupling options provide good access for circulator maintenance. One difference is that maintenance of IHX-B would require removal of the circulator in the case of the core-side coupling option (Option P1) assuming that the circulator is integrated with vessel, as shown. Alternatively, the circulator could be re-located to the reactor inlet piping (similar to Options S2 and S3).

Investment Risk

Two differences were noted relating to investment risk. The first, which relates to coolant chemistry and the potential for high temperature corrosion, concerns the plate-fin type IHX. With core-side coupling, the internal load bearing fins and brazed joints must be compatible with the PHTS coolant chemistry, which is more difficult to control, due to the presence of the core and graphite structures. A particular concern is degradation of the fins during extended normal operation, followed by a LOSP event that loads the fins in tension at high differential pressure. By contrast, shell side coupling places the internal fins on the SHTS side where coolant chemistry is likely to be more easily controlled. Further, the LOSP event loads the fins in compression, which is less likely to result in secondary failure. Note that, for the PCHE heat exchanger, there is no significant difference between the coupling options in terms of susceptibility to corrosion.

The second differentiating factor relates to circulating dust and the possibility of associated channel blockage and/or erosion. With shell-side coupling of the PHTS, dust would be more likely to “drop out” in the low velocity regions, prior to entering the heat exchanger shell-side passages. The significance of this difference would depend on the dust size and distribution.

3.4.2.4 Safety and Licensing

The only significant difference between the two coupling concepts with respect to safety and licensing is related to the LOSP event, and only for the plate-fin type heat exchanger. With core-side coupling, the LOSP event results in internal pressurization of the heat exchanger cores. With shell-side coupling, the LOSP event results in external pressurization and compressive loading. The implication is that the shell-side coupling option is less likely to experience a secondary failure. As previously seen with respect to investment risk, the PCHE heat exchanger is indifferent to the direction of LOSP loading.

3.4.2.5 Project Life Cycle Cost

Of the five attributes evaluated, modest differences were found in three. Differences in the maintainability characteristics of the two coupling options were evaluated to influence both design and development costs and operating costs. In both cases, the simpler maintenance concept of the shell-side coupling option was seen as an advantage. Economic risk was also seen as an advantage of the shell side coupling option, due to the reduced likelihood that a LOSP event would result in consequential damage.

3.4.3 Conclusions

Based upon the above evaluation, the following conclusions were reached regarding the core-side vs. shell-side coupling options:

1. Coupling option S2 is evaluated to be unacceptable.

In the S2 configuration, the straight reactor outlet pipe/hot gas duct provides a direct path from the reactor outlet plenum to the internal components of the heat exchanger. For this reason, coupling option S2 was evaluated to be unacceptable, due to the potential for neutron activation of the IHX-A metallic components, which are largely fabricated from cobalt-containing Alloy-617. Neutron activation of the IHX internal components would result in increased difficulty during maintenance.

2. Both the P1 and S3 coupling options are potentially acceptable.

At the level of the present evaluation, Options P1 and S3 are both viewed as being able to meet the requirements of Section 1.2. The following are seen as the major tradeoffs:

- For normal operation, a higher SHTS pressure favors P1 over S3, since the IHX heat exchange cores would operate in compression. Note that the direction of pressure bias is more significant for the plate-fin heat exchanger evaluated herein than for plate-type heat exchangers, such as the PCHE.
- Conversely, for the Loss of Secondary Pressure Event, the higher PHTS pressure would favor S3 over P1, regardless of the direction of the initial pressure bias.
- Option S3 offers the advantage of better access and a low-contamination environment for IHX maintenance, plus easier IHX-A removal.
- With the S3 coupling, if the PHTS is set at a higher pressure than the SHTS to maintain compression of the IHX cores during normal operation, leak detection would be faster (through SHTS radionuclide monitoring); however, contamination of the SHTS would result in the event of a leak.
- Option P1 offers advantage of a smaller overall system footprint, reduced piping (reduced piping losses) and flexibility for setting the PHTS circulator location
- With normal operating pressure biased to the SHTS side, small leaks would not result in SHTS contamination. This may allow continued operation in the presence of small leaks, and enable higher availability.

Overall, the scope of the present study did not provide the basis for a definitive selection of the P1 or S3 coupling options. To do so will require additional work to evaluate the significance of other influences. Such influences include, but are not limited to, building layouts, component integration and structural support provisions, the overall plant-level maintenance philosophy, evaluation of the likelihood of spurious IHX failures that could be addressed by maintenance versus common-mode failures (that would require the replacement of the entire heat exchanger) and further evaluation to confirm the feasibility of IHX maintenance activities (e.g., inspection and/or isolation of core modules via the central ducts).

In the interim, PBMR recommends the retention of coupling Option P1 as the basis for related conceptual design studies (e.g., Contamination Control). Final selection of the appropriate layout will be addressed during Conceptual Design, the scope of which would allow consideration of the multi-dimensional tradeoffs noted above.

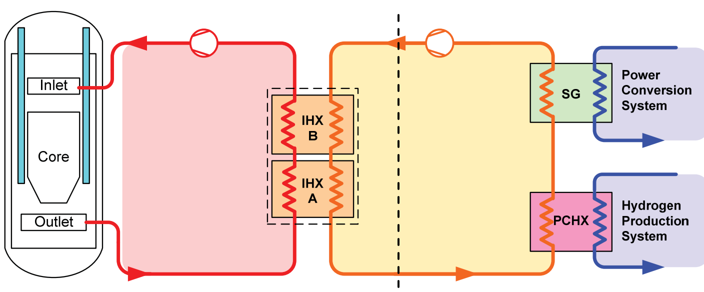
3.5 HTS Layout Evaluation

This section evaluates the implications of a single-loop Heat Transport System (HTS) versus multiple-loop heat transport systems. A HTS loop is defined as an "independent heat transport train" which implies that a single HTS loop has one reactor vessel outlet and one reactor vessel inlet; and that two HTS loops have two reactor vessel outlets and two reactor vessel inlets.

Section 3.5.1 presents the HTS options under consideration, Section 3.5.2 discusses the component–level considerations for a single-loop versus multi-loop HTS and Section 3.5.3 presents the system-level evaluation. The qualitative system-level evaluation considers development needs, operational performance, maintenance, safety and lifecycle cost. Recommendations are offered in Section 3.5.4.

3.5.1 HTS-Loop Layouts

Figure 3-10 and Figure 3-11, respectively, present a schematic and system layout for a single-loop and two-loop HTS. The IHX designs for these layouts are consistent with Concept C (Section 1.4.2.3) and Concept D (Section 1.7.1), respectively.



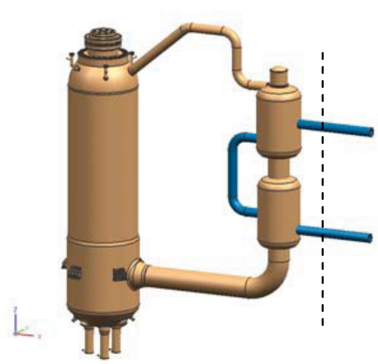


Figure 3-10 Single-Loop HTS

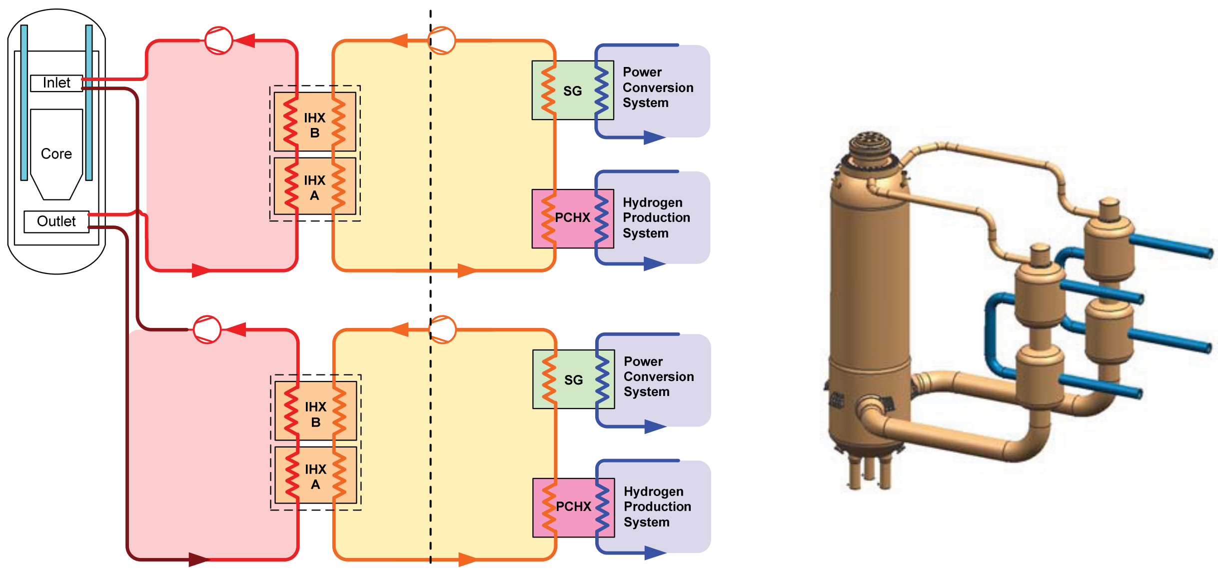


Figure 3-11 Two-Loop HTS

Both a single-loop and two-loop HTS could accommodate multiple parallel-coupled IHXs and/or multiple parallel-coupled SGs. An example showing multiple parallel-coupled IHXs is given in Figure 3-12 (only shown for single-loop). Note that the IHX design for the multiple parallel IHX configuration is consistent with Concept E (See Section 1.7.2). An example of multiple parallel-coupled SGs is shown in Figure 3-13 (also see Section 3.3).

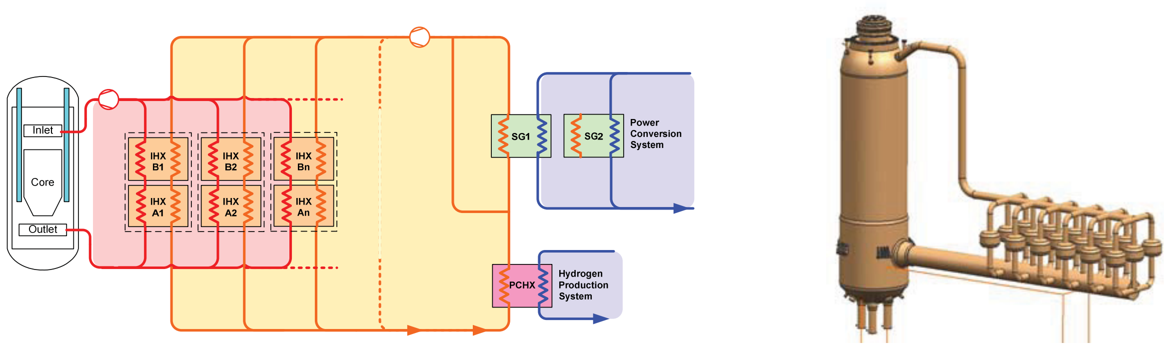


Figure 3-12 Single-Loop with Multiple IHXs in Parallel (Secondary Piping not Shown)

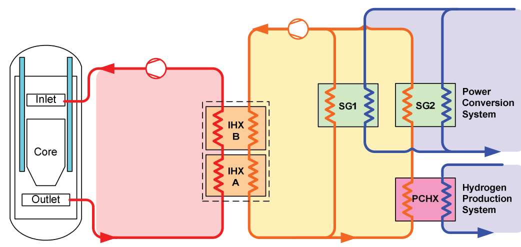


Figure 3-13 Single-Loop with Multiple SGs in Parallel

3.5.2 Component-Level Considerations

The main HTS components to be considered in the evaluation of single versus multiple heat transfer loops are the PBMR Reactor, Piping, IHX, Circulators, Steam Generator and the Process Coupling Heat Exchanger (PCHX).

3.5.2.1 PBMR Reactor

In order to meet the 2018 NGNP schedule and to reduce the risk and cost associated with FOAKE, it is proposed that the PBMR Reactor be as similar as possible to the existing PBMR DPP design. The existing PBMR DPP design has a single reactor outlet pipe and two reactor inlet pipes at the bottom of the reactor.

The maximum number of reactor outlet pipes that can be accommodated with the existing PBMR RPV geometry is three, spaced at 120° intervals. Although three reactor outlets are geometrically possible, it results in a less than optimum system and building layout and is, therefore, not recommended. Hence, only a single-loop and two-loop HTS is considered in this evaluation.

The reactor could accommodate two separate inlet/outlet pipes (two-loop configuration) or a single inlet/outlet pipe (one-loop configuration). However, the core outlet connections (Core Unloading Device, Fuel Handling and Support System, Reactor Outlet Pipe) are more complex than the core inlet connections and, from a reactor viewpoint, it is preferred to have a single outlet pipe in order to benefit from design maturity from the existing DPP design. Hence, the reactor would favor a single-loop configuration, but two-loops are also possible, at the expense of additional design changes.

3.5.2.2 Piping

The velocities in the reactor outlet pipe (1034 mm ID for the PCDR reference) are within acceptable limits. Though two-loops will result in two smaller reactor outlet pipes (or alternatively lower velocities and pressure losses for larger diameters), the costs are not expected to decrease significantly, given the diameter ranges under consideration. For the pipe diameters under consideration, the cost of piping is more influenced by the overall length of piping than the diameter differential; hence the cost of piping for the two-loop HTS is expected to be more expensive than for a single-loop. A multi-loop design requires a larger number of piping sections, which leads to more piping connections and welds, and, consequently, increased maintenance time (notably inspection). Hence, from a piping perspective, a single-loop configuration is preferred.

3.5.2.3 IHX

The IHX configuration selected in the assessment described in Section 1.6 has two rows of unit cell cores with the outlets on the tube side individually manifolded (Option C). In this configuration, a single IHX has a heat duty of 510 MWt, the IHX is split into high (IHX-A) and low temperature (IHX-B) sections, each of these sections is housed in a pressure vessel and the two vessels are connected in series. This IHX configuration is typical of a single-loop plant layout as shown in Figure 3-10.

For a two-loop plant layout, a different IHX design has been considered. This IHX design is very similar to the Option C design, described above, except that each IHX in the two-loop configuration has half of the heat duty (255 MWt) of Option C. For more details see Option D in section 1.7.1. Figure 3-11 shows a typical plant layout for this IHX design. Two internally cooled pipes from the reactor vessel lower section each feed a single 255 MWt IHX per loop. As in Option C, each IHX is split into high (IHX-A) and low temperature (IHX-B) sections, each of these sections is housed in a separate pressure vessel and the two vessels are connected in series. Four smaller pressure vessels are required for this option.

The two-loop IHX design (Option D) has the same positive features as the single-loop, Option C design, including a uniform flow distribution on the core side, primary-return "flex-pipes" from each core discharge header that provides axial and radial compliance, the potential for isolating and plugging a leaking core and an acceptable pressure drop associated with inlet and outlet core piping. Additionally, the single row of cores allows for simpler secondary side sealing and for a smaller size pressure vessel. Fabrication and transportation of this IHX should also be simpler than Option C. On the negative side, more material and fabrication time are required for the additional vessels and for the supports of the IHX within these vessels. Furthermore, the additional capital cost and complexity of two IHXs compared to one make this option less appealing than Option C.

A multiple parallel-coupled IHX design has also been proposed in Section 1.7.2 (Option E). The objective of this option was to further reduce the size of each IHX in order to improve the manufacturability, transportation, leak detection and replacement of a leaking IHX. The proposed design has the core arranged in a single row with vertical counter flows and has central primary supply and return and concentric secondary supply. The heat duty of each IHX was optimized to approximately 28 MWt, requiring eighteen heat exchangers to meet the plant heat duty of 510 MWt. A typical single-loop plant configuration for these IHXs connected in parallel is shown in Figure 3-12. There was no need to split the IHX core into high and low temperature sections because the detection and isolation or replacement of a leaking IHX is much easier without a large loss of plant output, assuming no common-mode failures. The costs associated with the increased number of vessels and piping required to connect them were also factors in selecting single-stage heat exchangers for this layout.

This multiple parallel design has the same positive features as Options C and D, including a uniform flow distribution at the core side, primary-return “flex-pipes” from each core discharge header providing axial and radial compliance and an acceptable pressure drop associated with inlet and outlet core piping. The pressure vessel size has been dramatically reduced, making its fabrication and transportation much simpler. On the negative side, the large number of vessels adds substantially to the capital cost and the layout requires a more extensive network of expensive actively cooled hot gas ducts/piping to accommodate the eighteen vessels. These negative attributes are viewed compelling, such that this single-loop multiple-IHX option was deemed less appealing than Option C. See Table 3-6 for more detailed evaluation.

In summary, since a single-series IHX (Option C) is viewed to be manufacturable and to have lower cost than multiple parallel units, a single-loop is preferred from the IHX perspective.

3.5.2.4 Circulator

The conceptual design and economic optimization of the circulator will dictate whether a radial circulator (single or multiple parallel) or an axial circulator (single or multiple parallel) is preferred. It is expected that two parallel circulators could be employed and operated in a single-loop configuration. Hence, it is assumed that either a single circulator or multiple parallel circulators could be accommodated in both a single and two-loop configuration with no clear preference for either option at this stage.

3.5.2.5 Steam Generator

The evaluation in Section 3.3 indicated that a single 520 MWt SG design has increased challenge and risk with respect to manufacturing, mainly due to the larger number of tube columns and larger diameter of the tube bundles, whilst the overall cost is estimated to be 30% lower than two 260 MWt SG designs. Since both designs can be manufactured with current technology, and with acceptable risk, a single 520 MWt design is preferred, due to lower cost.

3.5.2.6 Process Coupling Heat Exchanger

There do not seem to be any manufacturing or operational drivers that favor two 25 MWt PCHXs over a single 50 MWt design, or vice versa. From a cost viewpoint, two PCHXs would be more expensive than a single PCHX. The principal differences would be found in the vessels and piping connections. During a previous special study (Ref. 3-10), the WEC Team determined that 50 MWt was the minimum reasonable size to demonstrate a commercial decomposer. Hence, two 25 MWt units negates the original purpose of demonstrating the commercial 50 MWt unit.

3.5.2.7 Summary

A summary of HTS-loop configuration preferences from the component viewpoint is provided in Table 3-5. In general, a single loop configuration is preferred from the component viewpoint. However, a two-loop configuration would be also acceptable. The option of a single loop with multiple parallel-coupled IHXs was viewed as being not preferred from the piping and IHX viewpoints.

Table 3-5 Summary of HTS-Loop Component Preferences

Component	Single-Loop (IHX Concept C)	Two-Loop (IHX Concept D)	Single-Loop (IHX Concept E)
PBMR	Preference	OK	OK
Piping	Preference	OK	Not Preferred
IHX	Preference	OK	Not Preferred
Circulator	OK (TBC)	OK	OK
Steam Generator	Slight Preference	OK	OK
PCHX	Preference	Not Preferred	OK

3.5.3 Kepner-Tregoe System-Level Evaluation

A Kepner-Tregoe analysis was employed to facilitate the evaluation of single versus two-loop HTSs. For the single loop HTS, two variants were evaluated, one with a single IHX and one with multiple parallel IHXs. For the Kepner-Tregoe analysis, several criteria were identified in five main categories: design development, manufacturing and transportability, operation and maintenance, safety and investment protection, and lifecycle cost. As shown in Table 3-6, each category is weighted proportionally to its perceived importance, with the category weight divided among sub-criteria, based on the contribution of each criterion to the category.

In the detailed evaluation (Table 3-7), each criterion is rated for each case, based on the relative success with which the case met the criterion. The case meeting each criterion most successfully was awarded a rating of 10 with a proportionately lower rating awarded to the other cases based on their relative success in meeting that criterion. A score for each case in each criterion was calculated by multiplying the weight for each criterion by the rating for each case in that criterion. These scores were added for each case to give a resultant case score (Table 3-6).

Table 3-6 Kepner Tregoe HTS-Loop Evaluation Summary

			Single-Loop (Single-IHX) [Figure 3-10]		Two-Loop (Each Single IHX) [Figure 3-11]		Single-Loop (Multi-IHX) [Figure 3-12]	
Criteria	**Weight**	**Weight**	**Rating**	**Score**	**Rating**	**Score**	**Rating**	**Score**
1.0 Design/ Technology Development	**10.0**							
1.1 Similarity to DPP SSCs		0.30	10	30	6	18	10	30
1.2 Use of Developed Technologies		0.50	9	45	10	50	10	50
1.3 RISK - Design/ Technology Development		0.20	7	14	10	20	5	10
2.0 Manufacturing and Transportability	**15.0**							
2.1 Manufacturability and Constructability		0.40	7	42	10	60	9	54
2.2 Transportability		0.40	9	54	10	60	10	60
2.3 RISK - Manufacturing and Construction		0.20	8	24	10	30	9	27
3.0 Operation and Maintenance	**20.0**							
3.1 RAM (Reliability, Availability, Maintainability)		0.35	10	70	9	63	7	49
3.2 Performance and Operational		0.45	10	90	7	63	7	63
3.3 RISK - Operation and Maintenance		0.20	10	40	8	32	8	32
4.0 Safety and Investment Protection	**20.0**	**1.00**	**10**	**200**	**10**	**200**	**10**	**200**
5.0 Lifecycle Cost	**35.0**							
5.1 Design Development Cost (Non-recurring)		0.10	9	32	10	35	10	35
5.2 Capital Cost (Recurring)		0.25	10	88	6	53	5	44
5.3 Project Schedule		0.15	10	53	8	42	9	47
5.4 Operating Cost		0.30	10	105	8	84	8	84
5.5 RISK - Lifecycle Cost		0.20	10	70	10	70	10	70
Total	**100.0**	**5.0**		**956**		**880**		**855**

Table 3-7 Kepner Tregoe HTS-Loop Evaluation

Criteria	Single-Loop (Single IHX) Rating	Two-Loop (Two IHX) Rating	Single-Loop vs. Two-Loop HTS Discussion	Single-Loop (Multi-IHX) Rating	Single IHX vs. Multi IHX Discussion
Column Number	**[1]**	**[2]**	**[1] vs. [2]**	**[3]**	**[1] vs. [3]**
1.0 Design/ Technology Development	Better				
1.1 Similarity to DPP Reactor	10	6	Both options deviate from the DPP reactor design, due to inlet pipes at the top of the reactor. The DPP reactor has one COP and two CIPs. The single-loop has the advantage of keeping the core outlet connections same as DPP. A two-loop design with two COPs implies reactor design changes to other core outlet connections, notably the CUD that will need to be rotated to allow outlet piping connections.	10	Same reactor employed for both options.
1.2 Use of Developed Technologies	9	10	A two-loop design will result in smaller equipment designs. Both the SG assessment (Section 3.3) and IHX-Assessment (Section 5.2.3) has indicated that a single-unit component design is feasible. The detailed circulator design remains to indicate whether a single or parallel-unit design is preferred; though generally smaller units will probably be easier to develop.	10	Smaller vessel and circulator designs for multi-IHX option probably easier to develop.
1.3 RISK - Design/ Technology Development	7	10	The single-loop is viewed to have higher risk due to larger component designs, notably the circulator and SG.	5	The multiple-IHX option viewed to have lower risk due to smaller vessel and circulator designs; but increased overall risk due to development of complex coaxial T-junction piping.
2.0 Manufacturing and Transportability		Better			
2.1 Manufacturability and Constructability	7	10	It is estimated that a 520 MWt SG (single-loop) can be manufactured (Section 3.3), though it requires more development of special equipment. The single-loop IHX design is within current manufacturing capability and does not seem to impose any manufacturing challenges compared to smaller units (see Section 1.4.2). However, generally smaller components are expected to be easier to manufacture.	9	Smaller IHX vessels and circulators for multi-IHX option are easier to manufacture.
2.2 Transportability	9	10	The single-loop has larger components and is hence more challenging to transport; which also may effect site selection.	10	Smaller vessels for multi-IHX Option Easier to transport.

Table 3-7 Kepner Tregoe HTS-Loop Evaluation (cont'd)

Criteria	Single-Loop (Single IHX) Rating	Two-Loop (Two IHX) Rating	Single-Loop vs. Two-Loop HTS Discussion	Single-Loop (Multi-IHX) Rating	Single IHX vs. Multi IHX Discussion
Column Number	**[1]**	**[2]**	**[1] vs. [2]**	**[3]**	**[1] vs. [3]**
2.3 RISK - Manufacturing and Construction	8	10	The single-loop will require larger unit components and, hence, larger risk in manufacturing and construction.	9	Smaller risk in manufacturing and transport due to smaller equipment of multi-IHX option.
3.0 Operation and Maintenance	Better				
3.1 RAM (Reliability, Availability, Maintainability)	10	9	The single-loop has fewer welds and results in reduced inspection time. Generally, the availability is expected to be better for two-loops, but the reliability is expected to be better with a single-loop.	7	The single-IHX has fewer welds and results in reduced inspection time. Generally, the availability is expected to be better for multi-IHX, but the reliability is expected to be better with a single-IHX.
3.2 Performance and Operational	10	7	No discernable difference in performance is expected. The overall specs for single-loop seem simpler. Operation and control of the single-loop option is expected to be easier (no balancing required).	7	Operation and control of the single-IHX option is expected to be easier (no balancing required).
3.3 RISK - Operation and Maintenance	10	8	The single-loop is simpler and more reliable and hence viewed as a lower risk option from the O&M perspective.	8	The single-IHX option is simpler and more reliable and hence viewed as a lower risk option from the O&M perspective.
4.0 Safety and Investment Protection	10	10	Two-loops will have more welds and more HPB area, but both one and two loops should be acceptable. The two-loop option will have milder failure consequences (smaller transients); but is expected to have roughly double the probability of occurrence.	10	

Table 3-7 Kepner Tregoe HTS-Loop Evaluation (cont'd)

Criteria	Single-Loop (Single IHX) Rating	Two-Loop (Two IHX) Rating	Single-Loop vs. Two-Loop HTS Discussion	Single-Loop (Multi-IHX) Rating	Single IHX vs. Multi IHX Discussion
Column Number	**[1]**	**[2]**	**[1] vs. [2]**	**[3]**	**[1] vs. [3]**
5.0 Lifecycle Cost	**Better**				
5.1 Design and Technology Development Cost (Non-recurring)	**9**	**10**	The smaller (possibly simpler) designs associated with two-loop option could imply reduced development and testing costs. The overall design development effort is expected to be similar, but the two-loop option is expected to require more reactor (PBMR) design changes.	**10**	Multi-IHX with smaller blowers assumed to have reduced development costs.
5.2 Capital Cost (Recurring)	**10**	**6**	The two-loop is more complex with more components and, hence, expected to be more expensive, notably piping (Section 5.2.2) and SG (Section 3.3).	**5**	The multi-IHX is assumed to be more expensive due to additional vessels, T-junction piping, 18 circulators and interconnects.
5.3 Project Schedule	**10**	**8**	Multiple unit components are expected to be manufactured in sequence (notably circulators etc.) and, hence, the two-loop option is expected to result in longer manufacturing times.	**9**	Single-IHX and circulator expected to be manufactured in shorter time-frame than 18 IHXs and circulators.
5.4 Operating Cost	**10**	**8**	The higher reliability of a single-loop will translate into reduced operating costs, which is expected to outweigh improved maintenance benefits of the two-loop option.	**8**	The higher reliability of single-IHX will translate to reduced operating costs.
5.5 RISK - Lifecycle Cost	**10**	**10**	No discernable difference (fundamentally covered by risk and cost elements above).	**10**	

In summary, the single-loop HTS is less complex and should, therefore, be more easily licensed, controlled and operated. It is also more similar to the current DPP configuration, in that it has a single core outlet pipe. In addition, the capital cost is likely to be lower for a single loop. The two-loop option HTS has reduced technical risk, because the equipment sizes are smaller. Smaller equipment size will favor ease of manufacturing, construction and transportation. Overall, the single-loop HTS scored 9% better than the two-loop. However, this rating is very sensitive to assigned weights and ratings.

The two-loop HTS could be subject to a higher incidence of forced outages, due to the larger number of components and increased complexity. However, the consequences of each failure of the two-loop option are less severe with respect to transients induced, but both options would be designed for full life spectrum of the plant. The lower availability of the two-loop HTS, due to a higher incidence rate of forced outages, is based upon immediately shutting down both loops if one is inoperable, although this may not necessarily be the case; i.e. one loop might be operated for a period of time while the other is shut down. In either case, the reactor would probably need to be shut down and cooled before beginning repairs in order to create an acceptable maintenance environment. Also, if a plant were to be operated for a period of time with one loop out of service, it is likely that the plant would have to be shut down before re-starting the inactive loop to avoid an unacceptable thermal shock to the loop. Nevertheless, it may be possible to operate at partial loads while preparations for repairs are made. These considerations do not appear strong enough to alter the fundamental decision in favor of a one-loop option at this point.

Relative to the single-loop, single vs. multiple parallel IHX tradeoffs, the single-IHX is viewed to be more reliable, less complex (the most notable feature of the multiple parallel IHX HTS is the 18-leg coaxial T-junction core outlet pipe), less capital intensive and more easily controlled and operated than the multiple-IHX option. It is proposed to remain with a single IHX (which includes an IHX-A and IHX-B).

3.5.4 Recommendations

The component-level evaluation (Section 3.5.2) has indicated that all components, except circulator, prefer a single-loop HTS. The system-level evaluation has motivated that a single-loop option is preferred. Due to lower capital cost and system simplicity, it is recommended to remain with a single-loop, with a single IHX (with A and B sections), as the reference PBMR NGNP HTS design, pending new insights from future conceptual design activities.

3.6 References

3-1 Krischik, J., and B. Hiltgen, *The Klinger Hot Gas Double Axial Valve*, IAEA, April 1984.

3-2 Jansing, W., *Testing of High Temperature Components in KVK*, IAEA, April 1984.

3-3 *Valve to Connect the HTGR and Hydrogen Production System*, Persistent Quest Research Activities 2005, JAERI, 2005.

3-4 Nishihara, T., et al., *Development of High Temperature Isolation Valve for the HTTR Hydrogen Production System*, Nippon Genshiryoku Gakkai Wabun Ronbunshi, 3(4), 381 (2004) (in Japanese, but some data in English).

3-5 *NGNP and Hydrogen Production Preconceptual Design Report*, Section 6, Heat Transport System (NGNP-06-RPT-001, Rev0), Westinghouse Electric Company LLC, June 2007.

3-6 *NGNP and Hydrogen Production Preconceptual Design Report*, Section 8, Power Conversion System (NGNP-08-RPT-001, Rev0), Westinghouse Electric Company LLC, June 2007.

3-7 Steam Generator Subsystem Design Description (DOE-HTGR-86-129, Rev1)

3-8 Doosan SG Report (NGNP-RR-001)

3-9 *NGNP and Hydrogen Production Preconceptual Design Report*, NGNP-ESR-RPT-001, Revision 1, Westinghouse Electric Company LLC, June 2007.

3-10 NGNP and Hydrogen Production Preconceptual Design Report, NGNP-01-RPT-001, Special Study 20.7 – Hydrogen Production, January 2007.

4 DESIGN DATA NEEDS

Technology development needs in terms of DDNs for the IHX were identified in Ref. 1. This section presents a modified listing and description of the DDNs, based on recommendations given earlier in this report. In particular, the DDNs for Alloy 230 (HTS-01-07 through HTS-01-12) have been eliminated, based on the selection of Alloy 617 as the reference material for the high-temperature IHX (IHX-A). The designations for the DDNs addressing methods, modeling, performance verification, and ASME Code Cases (HTS-01-13 through HTS-01-19) remain as given in Ref. 1. DDNs addressed to Alloy 800H have been added, as this material has been selected for IHX-B. These and other new DDNs addressing Alloy 617, joining processes and assessment of Hastelloy XR are numbered HTS-01-20 through HTS-01-31.

A total of 25 active DDNs are now identified for the metallic IHX. These are listed, below, in Table 4-1. The updated DDNs, themselves, may be found in Appendix 2. They specifically address materials characterization and qualification, joining techniques for IHX assembly, development of methods and criteria for design and analysis, and performance verification for compact heat exchangers. In addition, DDNs are identified to support NGNP-specific ASME Code Cases for the IHX materials and design. Note, finally, that there is a great variation in the efforts that will be required for the various DDNs. Some will involve very considerable expense and time and some are basically complete, as will be indicated.

4.1 References

4-1 *NGNP and Hydrogen Production Preconceptual Design Report*, NGNP-ESR-RPT-001, Revision 1, Westinghouse Electric Company LLC, June 2007.

Table 4-1 Design Data Needs for Metallic IHX

DDN	Title
HTS-01	**Intermediate Heat Exchanger - Metallic**
HTS-01-01	Establish Reference Specifications and Procurement for Alloy 617
HTS-01-02	Thermal/Physical and Mechanical Properties of Alloy 617
HTS-01-03	Welding and As-Welded Properties of Materials of Alloy 617 for Compact Heat Exchangers
HTS-01-04	Aging Effects of Alloy 617
HTS-01-05	Environmental Effects of Impure Helium on Alloy 617
HTS-01-06	Grain Size Assessment of Alloy 617
HTS-01-07	Establish Reference Specifications and Procurement for Alloy 230 **[Deleted]**
HTS-01-08	Thermal/Physical and Mechanical Properties of Alloy 230 **[Deleted]**
HTS-01-09	Welding and As-Welded Properties of Materials of Alloy 230 for Compact Heat Exchangers **[Deleted]**
HTS-01-10	Aging Effects of Alloy 230 **[Deleted]**
HTS-01-11	Environmental Effects of Impure Helium on Alloy 230 **[Deleted]**
HTS-01-12	Grain Size Assessment of Alloy 230 **[Deleted]**
HTS-01-13	Methods for Thermal/Fluid Modeling of Plate-Type Compact Heat Exchangers
HTS-01-14	Methods for Stress/Strain Modeling of Plate-Type Compact Heat Exchangers
HTS-01-15	Criteria for Structural Adequacy of Plate-Type Compact Heat Exchangers at Very High Temperatures
HTS-01-16	Methods for Performance Modeling of Plate-Type Compact Heat Exchangers
HTS-01-17	IHX Performance Verification
HTS-01-18	Data Supporting Materials Code Case
HTS-01-19	Data Supporting Design Code Case
HTS-01-20	Influence of Section Thickness on Materials Properties of Alloy 617
HTS-01-21	Corrosion Allowances for Alloy 617
HTS-01-22	Establish Reference Specification for Alloy 800H
HTS-01-23	Supplemental High-Temperature Mechanical Properties of Alloy 800H
HTS-01-24	Effects of Joining Techniques on the Properties of Alloy 800H
HTS-01-25	Effects of Aging on the Properties of Alloy 800H
HTS-01-26	Effects of Exposure in Impure Helium on Alloy 800H Properties
HTS-01-27	Influence of Grain Size on Materials Properties of Alloy 800H
HTS-01-28	Influence of Section Thickness on Materials Properties of Ally 800H
HTS-01-29	Corrosion Allowances for Alloy 800H
HTS-01-30	Brazing and Diffusion Bonding Processes for Alloy 617 and Alloy 800H
HTS-01-31	Readiness Assessment for Hastelloy XR as an IHX Material

5 CONCLUSIONS AND RECOMMENDATONS

The Intermediate Heat Exchanger (IHX) and Heat Transport System (HTS) Conceptual Design Study has made a significant contribution to the advancement of the PBMR NGNP design. In particular, the study has provided enhanced insights into some of the more difficult issues pertaining to the HTS and its major components, especially the IHX.

The conclusions resulting from the IHX and HTS Conceptual Design Study are summarized in Section 5.1. Recommendations for further work are provided in Section 5.2.

5.1 Conclusions

The overall conclusions of the IHX and HTS Conceptual Design Study are summarized as follows:

8. The PCDR recommendation to utilize PCHE or PFHE compact heat exchanger technology as the basis for the IHX design has been confirmed through the present study.
9. A compact IHX configuration (applicable to both PCHE and PFHE heat exchangers) has been identified that potentially allows leak detection, location and isolation at the module-level.
10. Due to potential life limitations associated with high-temperature corrosion, the acceptability of a compact metallic IHX at 950°C remains to be confirmed. The present database for thin section materials is inadequate to support a definitive assessment.
11. The PCDR recommendation to separate the IHX into IHX-A and IHX-B sections, based on temperature, is supported by the results of the present study.
12. The PCDR recommendation to undertake a parallel development of ceramic HX technology for IHX A is confirmed by the present study.
13. The selection of core-side or shell-side coupling of the IHX to the PHTS requires additional system- and component-level information that is beyond the scope of the present study.
14. A single-loop HTS configuration is preferred, based both on component and system level considerations.

5.2 Recommendations

The following recommendations are provided with respect to future work:

5. Update the plant-level Functions & Requirements.

   It is particularly important that the NGNP mission be confirmed or redefined, along with the associated overall plant performance requirements. Especially important is the ultimate goal for the reactor outlet temperature (presently 950°C). It is noted that the present PBMR NGNP Preconceptual Design offers the flexibility to initially operate as an indirect steam-cycle or lower temperature process heat plant and then to evolve to higher temperatures.

6. Advance the overall NGNP Nuclear Heat Supply System (NHSS) integrated conceptual design, to better focus development of individual systems and components. To include:
    - Undertake a conceptual design study to develop and/or verify the combinations of insulation and active cooling provisions for the HTS.
        - A particular focus is assessing the feasibility of passive insulation for the SHTS and also its potential for the PHTS.
    - Develop HTS analytical models for the NHSS at a level sufficient to provide thermal/structural input to component designs, notably the IHX
        - Component conceptual designs (IHX, Blower, SG, PCHX etc) needed as input to HTS analytical models e.g., blower maps, mass of metal, etc. (iterative process).
    - With support of the respective vendors, develop the conceptual designs of the PCHE and PFHE to a level at which structural adequacy is established for normal operation and DBEs, notably including the LOSP event. Scope to include:
        - Iterative design and structural analyses
        - Develop an IHX maintenance philosophy and conceptual approach for inspection and maintenance that, as a minimum, includes consideration of:
            - Plant level availability and maintenance strategy/philosophy
            - The implications of leaks between the PHTS and SHTS as a function of the direction of pressure bias
            - The feasibility of heat transfer (HT) module isolation by plugging of lead-in/lead-out tubes
            - Heat transfer module isolation vs. IHX replacement
            - PHTS and SHTS helium purification system requirements/capabilities
        - Further develop the IHX/HTS coupling trade-offs (P1 vs. S3 vs. other) as input to overall system-level plant layout.
        - Support the development of detailed technology plans to address corrosion in thin metallic IHX sections and other high-priority DDNs (see Item 3, below)
    - With the support of a vendor, develop reference circulator concepts for the PHTS and SHTS.
    - With the support of a vendor, advance the reference SG design for the PCS.
    - Develop a plant-level maintenance strategy/philosophy as input to component maintenance.
    - Based on the above, optimize/propose a system-level layout following system-level and component design trade-offs.
    - Develop FOAK and NOAK cost estimates for major HTS components

7. Develop and implement detailed technology development plans to address high-priority DDNs, notably including (in priority order):
   - HTS-01-21 and HTS-01-29, Corrosion Allowances for Alloy 617 and Alloy 800H in thin sections
     - As necessary, develop detailed design/specifications for a corrosion test facility
     - Provide sufficient information (F&Rs, designs, cost, schedule, etc.) to allow a decision to proceed with development of the test facility and the conduct of testing.
   - HTS-01-30, Brazing and Diffusion Bonding Processes for Alloy 617 and Alloy 800H
   - HTS-01-18 and HTS-01-19, Data Supporting Materials and Design Code Cases
   - HTS-01-03 and HTS-01-24, Properties of Joints
   - Complete the design and initiate the construction of a heat transfer test facility to support confirmatory IHX performance and integrity tests at the module level (HTS-01-17)

8. Establish a parallel effort to design and develop ceramic heat exchangers, as outlined in the PCDR.

BIBLIOGRAPHY

None. References are provided in individual sections.

DEFINITIONS

None

REQUIREMENTS

Requirements are provided in Section 1.2.

LIST OF ASSUMPTIONS

The following assumptions served as a basis for this report:

1. Except as otherwise noted, the work within this report is based upon the functions, requirements, configuration and operating parameters recommended in the PBMR NGNP Preconceptual Design Report. These specifically include a 500 MWt power level, 950°C reactor outlet temperature, 350°C reactor inlet temperature and a primary heat transport system (PHTS) pressure of 9MPa.
2. The assessment was limited to metallic heat exchangers.

TECHNOLOGY DEVELOPMENT

Technology Development is addressed in Section 4.

APPENDIX 1: BRAZING CONSIDERATIONS AND LITERATURE SURVEY

BRAZING CONSIDERATIONS AND LITERATURE SURVEY

Johan Markgraaf Sr., M-Tech Industrial

The most important characteristic of Nicrobraze LM, Nicrobraze 30, and other Ni-based filler metals is their relatively high content of boron (3.1 % in Nicrobraze LM ≡ AWS BNi2 ≡ AMS 4777), phosphorous and/or silicon (17% in Nicrobraze 30 ≡ AWS BNi5, ≡ AMS 4782) content to reduce the melting temperatures of the Ni and Ni-Cr matrix to suitable brazing temperatures, and to ensure acceptable wetting and flow behavior. However, these alloying elements lead to the formation of hard brittle intermetallic compounds, such as Ni borides or Cr silicides within the brazing joint that reduce the joint strength if not correctly brazed or post-brazed heat-treated. Furthermore, it is reported that another negative effect of these brittle phases is a local reduction in corrosion resistance of brazed joints due to Cr-depletion [1]. The Ni-based brazing alloys are also not easily worked to sheet form and are therefore only produced in powder or amorphous melt-spun foil also known as amorphous brazing foil (ABF), of which the latter may be more applicable to core brazing of the IHX.

A literature survey to determine ongoing efforts in this area showed that several but limited studies have been conducted in an effort to control (or eliminate) the formation of the brittle phases or to optimize the integrity of the brazements of thin sections.

Rabinkin [2] e.g., used MBF-20 Ni-based amorphous brazing foils (AWS ANSUA 5.8 Specification for BNi2 classification) with an average thickness of 0.025, 0.037 and 0.05 mm, respectively as braze fillers, to successfully join 0.5 mm thick sinusoidal shaped fins to 0.1 mm thick flat plates all produced from UNS4360 stainless steel, in a plate-fin heat exchanger. Loaded samples were placed in a vacuum furnace and brazed at a temperature of approximately 1090 °C for 15 minutes, which resulted in a plurality of sealed channels. Although the material used is not a Ni-base alloy proper, this work illustrates the advantages of the use of foil.

It was found (op. cit.) that the joint thickness in the middle portion of non-constrained brazes was the same, regardless of the thickness of the virgin amorphous foil. Excessive molten MBF-20 metal, particularly in the case of the 50 μm foil, flowed out of the initial gaps and climbed up on the fin walls resulting in wider cross-sections and larger fillets without the formation of detrimental narrow cavity-like crystallization shrinkage patterns (that may initiate crevice corrosion). I-beam shaped brazed samples were tested at 650 °C using standard tensile testing procedures. The filler foil with a thickness of 50 μm resulted in the highest maximum load before failure (of 537 kg) compared to foils with a thickness of 37μm and 25 μm respectively in this work.

Rabinkin [2] also reported on the development of brazing filler metals based on a modified MBF-51 (BNi-5b) alloy containing 5 wt % Mo added to the (Ni,Cr)-base and a low-boron containing Co-based MBF-100 series (21Cr4,5W7,3Si1,4B with 3-5% Pd) capable of withstanding the severe service conditions of jet engines operating at 1200 °C. The developed MBF-100 series were tested in joining and repair of vanes and blades made of superalloys and by brazing honeycomb cores made of e.g., (Ni,Cr,Co)-based MSRR 7248 (CMSX-4) and Inconel 738 superalloys to face plates. It was claimed that the specific advantages of these alloys included the ability to braze at high temperatures and to provide brazements that can be used at elevated temperature in a high oxidation and corrosive environment, without any significant degradation of mechanical properties. In terms of corrosion resistance, it was found that the joint corrosion and oxidation resistances increase along the ABF series of Ni-based alloys in the order Ni-based with Mo additions -, Co/Ni-based, and Co/Ni-based with Pd additions.

Applying a moderate compressive load (≈10 MPa) to components during brazing seems to be beneficial to obtaining increased join strength because it is thought that the liquid phase enriched with melting temperature depressants is ejected out of the brazing joint, resulting in the disappearance of brittle, and an increase in ductile, phases. Yeh and Chuang [3] brazed sample strips of superplastic Inconel 718 with Ni-P and Ni-Cr-P filler foils to study the effects of applied pressure on the bonding strength, microhardness, and corrosion resistance. Results of this work showed that the brazements with Ni-Cr-P filler metal have higher bonding strength (and corrosion resistance) than those with Ni-P filler metal using the conventional brazing method, without applied pressure. When brazing was conducted under applied pressure, the bonding strength increased with applied pressure for the brazements with both filler metals.

Traditionally, long brazing times or heat treatment after solidification is used to reduce or avoid hard phase formation. Short diffusion distances for boron, silicon, or phosphorous are advantageous so, that from a construction viewpoint, small brazing gaps (<0.05 mm) are required that lead to an increase in costs.

Luchscheider and Humm [4] reported on the use of Hf, as a melting-point depressant to producing ductile Ni-based filler metals with moderate brazing temperatures below 1240°C. The basis of their (op. cit.) filler metal development is the Ni-Hf eutectic on the Ni-side of this binary system that includes the incongruently melting compound Ni5Hf. It is reported that compared to borides with a microhardness of 2000 – 2600 HV0.05 , the Ni5Hf-phase has a microhardness of 400 HV0.05 , and this promised relatively good ductile behavior. Cr, Mo, Co and Ti were added in order to improve the wetting and mechanical properties. The best wetting and flow behavior on stainless steel and Inconel 600 substrates was obtained using brazing temperatures of 1235 °C and a vacuum of less than 2x10-4 mbar. No brittle phases were formed during brazing using rollable filler metals (e.g., Ni10Hf13Cr, Ni7Hf13Cr, and Ni5Hf13Cr) that possess high tolerances in terms of brazing gaps. Tensile strengths of the order of 517 MPa were obtained for Inconel 600 brazed with Ni15Hf13Cr, - tested according to DIN 8525, with a brazing gap of between 50 – 70 μm, also showing that the tensile strength of the brazed joint increases with decreasing joint space. However, TGA results showed that the oxidation resistance of these filler metals was poorer than that of the Inconel base material. Oxidized at 1015°C for 16 hours, the weight gain of all Hf-containing filler metals were at maximum about 1mg/cm2 with Ni-15Hf-13Cr, the lowest at about 0.5 mg/cm2.

Perhaps the use of the palladium-bearing filler metals without the additions of B or Si (e.g., Pd54-Ni36-10Cr,) should also be considered, since it is claimed that they promote joints with good mechanical integrity and freedom of the formation of brittle intermetallics, because Pd forms solid solutions with the most common metals.

Bose et al. [5] have studied the fundamental aspects of "high strength nickel-palladium-chromium brazing alloys". Mechanical properties, corrosion behavior and microstructural characteristics of joints prepared with these filler metals are compared to BAu-4 joints and recommendations on optimum alloy compositions were derived.

Yu, Liaw and Shiue [6] brazed Inconel 601 using a 70Au-22Ni-8Pd braze alloy. The infrared brazed joint was primarily comprised of Au-rich and Ni-rich phases and no interfacial intermetallic compound was observed. They reported that, with increasing the brazing temperature and/or time, the microstructure of the brazed joint was coarsened. Shear strength of 362 MPa was obtained for the joint infrared brazed at 1050°C for 180 s, which was higher than that obtained by furnace braze methods.

In a US patent (WO/2002/022299) it is claimed that a post-braze 400°C heat treatment conditioning step will result in lower leach rates of Ni in water-cooled heat exchangers produced from stainless steels if brazed with the filler metals (e.g., BNi-2, BNi-5 etc.) referred to in ANSI classification A8.5 (per AWS) – possibly of value to these discussions.

Miglietti [7] studied the correlation between microstructure and mechanical properties of diffusion brazed MAR-M 247 using 100 μm thick filler foil (Ni-15Cr-3,5B) with the purpose of eliminating the formation of brittle phases by variation of temperature and time during processing. The results demonstrated that diffusion brazed joints had equivalent mechanical strength to that of the parent metal.

Literature searches with Scopus, Science Direct, Engineering Village and Google returned hardly any information to assist with estimating long-term properties or corrosion of brazed joints of Alloys 617 or 800H using any filler metals.

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APPENDIX 2: DESIGN DATA NEEDS

DDN HTS-01-01 ESTABLISH REFERENCE SPECIFICATIONS AND PROCUREMENT OF ALLOY 617

1. Assumptions (to be confirmed by meetings with alloy vendor organizations and related R&D)

The standard American Society for Testing and Materials (ASTM) specification for Alloy 617 can be modified slightly to produce an alloy with more predictable high temperature mechanical properties optimized for the IHX application or the standard ASTM Alloy 617 specification will be selected for procurement and qualification testing. The alloy chemistry, fabrication processes and grain size have the most significant impact on long-term properties.

2. Current Database Summary

The current database for Alloy 617 shows a fairly wide variation of high temperature mechanical properties for the material heats that have been examined in detail. Factors that could have caused the observed variation of properties include (a) the material heats were produced over many years and significant changes have occurred in melting and forging practices over that time; (b) the standard ASTM chemical specification for this alloy is fairly broad for various reasons; and (c) the specific testing procedures used have changed over the time-span involved. An effort was made within the NGNP Materials R&D Program at ORNL to produce a refined specification; however, due to a lack of program funding and problems with forging the test heats, the results obtained were also not conclusive. It is known that the French have incorporated Alloy 617 in their IHX testing and are performing R&D on a more refined specification.

3. Summary of Data Needed

Data needed include assessment of the current database and verification that at least three heats obtained for the IHX testing and qualification program conform to the procurement and quality assurance documentation.

4. Designer’s Alternatives

Alloy 230 could be selected on the basis of DDNs HTS-01-07 through HTS-01-12 without a qualification R&D program for Alloy 617.

5. Selected Design Approach and Explanation

The proposed approach is to obtain an adequate database for design, analysis and test evaluation of compact heat exchangers using Alloy 617 with a refined purchase specification and to support the development of ASME Section III Code Cases for the material and design.

6. Schedule Requirements

Establishing the reference alloy specification, alloy procurement and verification are required prior to the start of testing, qualification, modeling or ASME Code development. Therefore, this is needed as soon as possible, but not later than the first half of FY 2009.

7. Priority

Urgency (1-5):	1
Cost-Benefit (Low, Medium, High):	High
Uncertainty in Existing Data (Low, Medium, High):	High
Importance of New Data (Low, Medium, High):	High

8. Fallback Position and Consequences Of Non-Execution

The fallback position is to select a shell and tube IHX design that would allow use of standard Alloy 617. Non-execution of this DDN would, therefore, eliminate the option for using a compact IHX design and result in unacceptable performance and higher cost

9. References

1. NGNP and Hydrogen Production Preconceptual Design Report, NGNP-01-RPT-001, *Special Study 20.3 - High Temperature Process Heat Transfer and Transport*, January 2007.
2. Ren, W. and Swindeman, R. W., *Assessment of Existing Alloy 617 Data for GEN IV Materials Handbook*, ORNL/TM-2005/510, Oak Ridge National Laboratory, Oak Ridge, TN, June 30, 2005.

DDN HTS-01-02 THERMAL/PHYSICAL AND MECHANICAL PROPERTIES OF ALLOY 617

1. Assumptions (to be confirmed by the related R&D program)

Alloy 617, optimized for compact heat exchangers with a small grain size (ASTM 6-8), will have mechanical properties that are adequate for a plate-type IHX operated under NGNP conditions.

2. Current Database Summary

The current mechanical and physical properties database for Alloy 617 is based primarily on multiple heats of standard ASME SB-168 plate material with a relatively large grain size (ASTM 0-3), and this is not consistent with the needs of compact heat exchangers. The database is reasonably complete for the temperature range of room temperature to 982ºC. Standard Alloy 617 is listed in ASME Section II for application to ASME Sections I and VIII, Division 1. The ASME does not currently allow Alloy 617 for Section III applications and it is anticipated that a Section III Code Case would need to be submitted and approved for a nuclear power application to be implemented using this material. The material would be exposed to an inlet temperature of about 950ºC and operate for extended time periods at this temperature; therefore, creep and other high temperature mechanical properties are of particular importance.

3. Summary of Data Needed

Data needed include thermal/physical properties (chemical composition, thermal conductivity and coefficient of thermal expansion and mechanical properties (elastic constants, stress/strain relationships, fatigue and creep strength, fracture toughness, etc.) at temperatures up to 1000ºC on three heats of fine grained material.

4. Designer's Alternatives

The designer's alternative is to select an IHX design that does not require a thin-section material, such as a shell and tube IHX.

5. Selected Design Approach and Explanation

The proposed approach is to obtain an adequate database for design, analysis and test evaluation of compact heat exchangers using Alloy 617 with a refined purchase specification and to support the development of ASME Section III Code Cases for the material and design.

6. Schedule Requirements

Results are required by the end of FY2010 to support design, procurement and testing of a prototype IHX module for verification of models prior to long-lead procurement of NGNP components in FY2013, which is required to support NGNP operation by the end of 2018.

7. Priority

Urgency (1-5):	1
Cost-Benefit (Low, Medium, High):	High
Uncertainty in Existing Data (Low, Medium, High):	High
Importance of New Data (Low, Medium, High):	High

8. Fallback Position and Consequences Of Non-Execution

The fall-back position is to select a shell and tube IHX design that would allow use of standard Alloy 617. Non-execution of this DDN would, therefore, eliminate the option for using a compact IHX design with unacceptable performance and cost ramifications.

9. References

1. NGNP and Hydrogen Production Preconceptual Design Report, NGNP-01-RPT-001, *Special Study 20.3 - High Temperature Process Heat Transfer and Transport*, January 2007.

DDN HTS-01-03 WELDING AND AS-WELDED PROPERTIES OF MATERIALS OF ALLOY 617 FOR COMPACT HEAT EXCHANGERS

1. Assumptions (to be confirmed by the related R&D program)

Alloy 617 can be welded by conventional processes and diffusion bonded and brazed as thin sheets to form a prototype compact heat exchanger, provided that alloy chemistry, fabrication processes and welding/diffusion bonding processes are closely controlled.

2. Current Database Summary

The current database for Alloy 617 includes extensive information on conventional welding processes. Therefore, the weldability assessment will validate that conventional welding processes can be performed successfully on the alloy heats procured. The current database includes very little information on thin sheet diffusion bonding or brazing, which are essential technologies required for the fabrication of some types of compact heat exchangers. The information available indicates that Alloy 617 can be diffusion bonded with a thin nickel interface layer with some loss in mechanical properties. Heatric is undertaking the development of diffusion bonding of Alloy 617; however, this information is proprietary and has not been released and could not be used in the ASME Code Case even if it was obtained under a proprietary agreement.

3. Summary of Data Needed

Data needed include selected mechanical properties (yield, tensile strength and elongation; fatigue and creep strength; fracture toughness, etc.) at temperatures up to 1000ºC on welded and diffusion bonded test specimens and validation that diffusion bonding can be performed without using an interface material and without a significant reduction in mechanical properties.

4. Designer’s Alternatives

The designer’s alternative is to select an IHX design that does not require a thin-section material, such as a shell and tube IHX.

5. Selected Design Approach and Explanation

The proposed approach is to obtain an adequate database for design, analysis and test evaluation of compact heat exchangers using Alloy 617 with refined purchase specifications and to support the development of ASME Section III Code Cases for the material and design.

6. Schedule Requirements

Results are required in early-FY2010 to support design, procurement and testing of a prototype IHX module for verification of models prior to long-lead procurement of NGNP components in FY2013, which is required to support NGNP operation by the end of 2018.

7. Priority

Urgency (1-5):	1
Cost-Benefit (Low, Medium, High):	High
Uncertainty in Existing Data (Low, Medium, High):	High
Importance of New Data (Low, Medium, High):	High

8. Fallback Position and Consequences Of Non-Execution

The fallback position is to select a shell and tube IHX design that would allow use of standard Alloy 617 and conventional welding processes. Non-execution of this DDN would, therefore, eliminate the option for using a compact IHX design with unacceptable performance and cost ramifications.

9. References

1. NGNP and Hydrogen Production Preconceptual Design Report, NGNP-01-RPT-001, *Special Study 20.3 - High Temperature Process Heat Transfer and Transport*, January 2007.

DDN HTS-01-04 AGING EFFECTS OF ALLOY 617

1. Assumptions (to be confirmed by the related R&D program)

Alloy 617 can be used at very high temperatures (up to 950ºC) for very long time periods (at least 10 years), without unacceptable degradation of mechanical properties or microstructure if alloy chemistry, fabrication processes and grain size are closely controlled.

2. Current Database Summary

The current database for Alloy 617 contains extensive information on the aging characteristics of plate material tested in an air environment. This information indicates that the effects of long term aging on mechanical properties and microstructure show some variability, primarily as a function of slight changes in alloy chemistry and test conditions; however, most data shows a small increase in tensile properties and creep resistance at intermediate temperatures (600-800ºC) with a corresponding decrease in fracture toughness and ductility. Less data is available for long-term exposure at higher temperatures (up to 950ºC); however, more microstructural changes were noted and most mechanical properties showed limited degradation as a function of time and temperature. Essentially no data is available for the aging characteristics of welded, brazed or diffusion bonded material.

3. Summary of Data Needed

Data needed include selected mechanical properties (yield, tensile strength and elongation; fatigue and creep strength; fracture toughness, etc.) following aging at temperatures up to 1000ºC for times up to 10,000 hours on standard, welded, brazed, and diffusion bonded test specimens and validation that aging does not produce an unacceptable reduction in mechanical properties.

4. Designer's Alternatives

The designer's alternatives are limited because aging changes occur for all heat exchanger designs if Alloy 617 is used as the primary fabrication material and these changes need to be evaluated.

5. Selected Design Approach and Explanation

The proposed approach is to obtain an adequate database for design, analysis and test evaluation of compact heat exchangers using Alloy 617 with refined purchase specifications and to support the development of ASME Section III Code Cases for the material and design.

6. Schedule Requirements

Results are required by the end of FY2010 to support design, procurement and testing of a prototype IHX module for verification of models prior to long-lead procurement of NGNP components in FY2013, which is required to support NGNP operation by the end of 2018.

7. Priority

Urgency (1-5):	1
Cost-Benefit (Low, Medium, High):	High
Uncertainty in Existing Data (Low, Medium, High):	High
Importance of New Data (Low, Medium, High):	High

8. Fallback Position and Consequences Of Non-Execution

The fallback position is to use the existing database and not proceed with an Alloy 617 Code Case.

9. References

1. NGNP and Hydrogen Production Preconceptual Design Report, NGNP-01-RPT-001, *Special Study 20.3 - High Temperature Process Heat Transfer and Transport*, January 2007.

DDN HTS-01-05 ENVIRONMENTAL EFFECTS OF IMPURE HELIUM ON ALLOY 617

1. Assumptions (to be confirmed by the related R&D program)

Alloy 617 can be used at very high temperatures (up to 950ºC) for very long time periods (at least 10 years) without unacceptable degradation of mechanical properties or microstructure in a slightly impure helium environment containing CO, CO_2, H_2, H_2O and O_2, if alloy chemistry, fabrication processes and control of the helium environment in the reactor are maintained.

2. Current Database Summary

The current database for Alloy 617 contains limited information on the corrosion, microstructural stability and mechanical property changes that may occur as a function of time, temperature and environmental conditions following long term high temperature exposure to an impure helium environment. These data show substantial variability due primarily to slight differences in alloy chemistry and specific testing conditions. These data also indicate that surface effects, including carburization or decarburization, can occur during the testing performed and these changes can affect the high temperature mechanical properties of the alloy. The database contains little or no information on the effects of long-term environmental exposure at very high temperature on welded, brazed or diffusion bonded specimens. Aging and environment effects on Alloy 617 are closely related.

3. Summary of Data Needed

Data needed include selected mechanical properties (yield, tensile strength and elongation; fatigue and creep strength; fracture toughness, etc.) following aging and environmental exposure at temperatures up to 1000ºC on standard, welded and diffusion bonded test specimens and validation that aging and environmental exposure do not produce an unacceptable reduction in mechanical properties.

4. Designer's Alternatives

The designer's alternatives are limited because aging and environmentally induced changes occur for all heat exchanger designs if Alloy 617 is used as the primary fabrication material and helium is used as the Very High Temperature Reactor (VHTR) coolant; therefore, these changes need to be evaluated irrespective of heat exchanger design.

5. Selected Design Approach and Explanation

The proposed approach is to obtain an adequate database for design, analysis and test evaluation of compact heat exchangers using Alloy 617 with refined purchase specifications and to support the development of ASME Section III Code Cases for the material and design.

6. Schedule Requirements

Results are required by the end of FY2010 to support design, procurement and testing of a prototype IHX module for verification of models prior to long-lead procurement of NGNP components in FY2013, which is required to support NGNP operation by the end of 2018.

7. Priority

Urgency (1-5):	1
Cost-Benefit (Low, Medium, High):	High
Uncertainty in Existing Data (Low, Medium, High):	High
Importance of New Data (Low, Medium, High):	High

8. Fallback Position and Consequences Of Non-Execution

The fallback position is to use the existing database and not proceed with an Alloy 617 Code Case.

9. References

1. NGNP and Hydrogen Production Preconceptual Design Report, NGNP-01-RPT-001, *Special Study 20.3 - High Temperature Process Heat Transfer and Transport*, January 2007.
2. Ren, W. and Swindeman, R. W., *Assessment of Existing Alloy 617 Data for GEN IV Materials Handbook*, ORNL/TM-2005/510, Oak Ridge National Laboratory, Oak Ridge, TN, June 30, 2005.

DDN HTS-01-06 GRAIN SIZE ASSESSMENT OF ALLOY 617

1. Assumptions (to be confirmed by the related R&D program)

Alloy 617 can retain acceptable fatigue and creep properties at high temperature for long time periods if the alloy chemistry and fabrication processes are carefully controlled. A key aspect of the control of fabrication processes includes the initial procurement of fine grain size material (ASTM 6-8). It is also assumed that a reasonably fine grain size can be maintained following diffusion bonding and high temperature long-term exposure.

2. Current Database Summary

The current database for Alloy 617 was primarily obtained using test specimens with a large grain size (ASTM 0-3). This range of grain size was used because this alloy was developed to optimize high temperature creep resistance and a large grain size will enhance this property. Virtually all creep testing performed previously was performed at relatively high stress levels and it was assumed that the deformation mechanism under these conditions was power law creep. The preferred IHX design for the NGNP is currently a compact type high efficiency heat exchanger that is fabricated from thin sheets of material that are subjected primarily to very low stresses over long time periods. This issue was recently evaluated by ORNL and it was concluded that under these conditions a different deformation mechanism (Nabarro-Herring creep) could dominate and this could result in the prediction of lower creep rates during testing by several orders of magnitude if a power law mechanism was used to evaluate the data rather than the alternate mechanism noted. The use of thin sheets for the fabrication of a compact type of IHX will require the use of smaller grain size material to increase fatigue resistance during operation and to reduce the possibility that grains approaching or greater than the sheet thickness will be present during fabrication. Therefore, because of these issues, much of the current database for Alloy 617 could be inapplicable for the current IHX application.

3. Summary of Data Needed

Data needed include the evaluation of creep, creep fatigue and fatigue properties of fine grained material; the determination of the specific mechanism that is applicable for the evaluation of data under the conditions of low stress creep testing and the investigation of the effects of diffusion bonding and long-term high temperature exposure on the residual grain size of the material.

4. Designer's Alternatives

The designer's alternative is to select an IHX design that does not require a thin-section material, such as a shell and tube IHX.

5. Selected Design Approach and Explanation

The proposed approach is to obtain an adequate database for design, analysis and test evaluation of compact heat exchangers using Alloy 617 with refined specifications and to support the development of ASME Section III Code Cases for the material and design.

6. Schedule Requirements

Results are required in early-FY2010 to support design, procurement and testing of a prototype IHX module for verification of models prior to long-lead procurement of NGNP components in FY2011, which is required to support NGNP operation by the end of 2018.

7. Priority

Urgency (1-5):	1
Cost-Benefit (Low, Medium, High):	High
Uncertainty in Existing Data (Low, Medium, High):	High
Importance of New Data (Low, Medium, High):	High

8. Fallback Position and Consequences Of Non-Execution

The fallback position is to use the existing database, not proceed with an Alloy 617 Code Case and use a traditional heat exchanger design.

9. References

1. NGNP and Hydrogen Production Preconceptual Design Report, NGNP-01-RPT-001, *Special Study 20.3 - High Temperature Process Heat Transfer and Transport*, January 2007.

DDN HTS-01-13 METHODS FOR THERMAL/FLUID MODELING OF PLATE-TYPE COMPACT HEAT EXCHANGERS

1. Assumptions (to be confirmed by the related R&D program)

Thermal structural modeling, for quasi-steady state and transient analyses, is required to provide a predictive basis for operation and performance characteristics of a plate type IHX. A suitable model will need to be developed for this task. The data obtained during the execution of DDNs for Alloy 617 and Alloy 800H will need to be input into the model to provide a physical and mechanical design basis for the IHX alloy selected. The predictive output from the model will be compared and modified as appropriate, based on the results of prototype IHX testing and other verification and validation activities. These results will form the basis for development of the ASME Code Case for the alloy and IHX design selected. Some type of simplified modeling techniques or the development of specific modeling test specimens may be required due to the complexity of the model required.

2. Current Database Summary

The physical and mechanical properties database for the potential IHX structural alloys will be developed during the execution of DDNs for Alloy 617 and Alloy 800H. Other aspects of model development will be based on known finite element analysis (FEA) modeling techniques and known mathematical relationships of the selected IHX structure as a function of gas temperature, fluid flow, interface conditions, structural stresses and other factors. This assumes that a heat exchanger design not currently covered in ASME Section III or Section VIII is used. This includes all heat exchanger designs that are not variants of tube and shell design types. An actual design database required for ASME fabrication of a plate type compact heat exchanger is not available and will be developed in DDNs HTS-01-13 through HTS-01-16 and become a part of the ASME Code Case (DDNs HTS-01-18 and HTS-01-19).

3. Summary of Data Needed

Data needed include all information required to validate the operational and design basis of the plate type heat exchanger design selected, all information required to develop a theoretical design basis for comparison with empirical data resulting from the prototype IHX testing performed in response to DDN HTS-01-17 and all information required to perform verification and validation of the analytical model developed.

4. Designer's Alternatives

The designer's alternative is to select an IHX design that utilizes an existing ASME design basis, such as a shell and tube IHX.

5. Selected Design Approach and Explanation

The proposed approach is to obtain an adequate database for design, analysis and test evaluation of compact heat exchangers using the selected structural alloy and to support the development of ASME Section III Code Cases for the material and design.

6. Schedule Requirements

Final results are required by the middle of FY2011 to support design, procurement and testing of prototype IHX modules prior to long-lead procurement of NGNP components in FY2013 and to support ASME Code Case development activities. All activities are required to support NGNP operation by the end of 2018.

7. Priority

Urgency (1-5):	1
Cost-Benefit (Low, Medium, High):	High
Uncertainty in Existing Data (Low, Medium, High):	High
Importance of New Data (Low, Medium, High):	High

8. Fallback Position and Consequences Of Non-Execution

The fallback position is to use the existing ASME design database and use an ASME Code approved heat exchanger design and material for the IHX application.

9. References

1. NGNP and Hydrogen Production Preconceptual Design Report, NGNP-01-RPT-001, *Special Study 20.3 - High Temperature Process Heat Transfer and Transport*, January 2007.

DDN HTS-01-14 METHODS FOR STRESS-STRAIN MODELING OF PLATE-TYPE COMPACT HEAT EXCHANGERS

1. Assumptions (to be confirmed by the related R&D program)

Stress-strain structural modeling is required to provide a predictive basis for operation and performance characteristics of a plate type IHX. A suitable model will need to be developed and data obtained during the execution of DDNs for Alloy 617 and Alloy 800H will need to be input to provide a physical and mechanical design basis for the IHX alloy selected. The predictive output from the model will be compared and modified, as appropriate, based on the results of prototype IHX testing and verification and validation activities. These results will form the basis for development of the ASME Code Case for the alloy and IHX design selected. Some type of simplified modeling techniques or the development of specific modeling test specimens may be required due to the complexity of the model required.

2. Current Database Summary

The physical and mechanical properties database for the potential IHX structural alloys will be developed during the execution of DDNs for Alloy 617 and Alloy 800H. Other aspects of model development will be based on known finite element analysis (FEA) modeling techniques and known mathematical relationships of the selected IHX structure as a function of gas temperature, fluid flow, interface conditions, structural details and other factors, assuming that a heat exchanger design not currently covered in ASME Section III or Section VIII is used. This includes all heat exchanger designs that are not variants of tube and shell design types. An actual design database required for ASME fabrication of a plate type compact heat exchanger is not available and will be developed in response to DDNs HTS-01-13 through HTS-01-16 and will become a part of the ASME Code Case (DDNs HTS-01-18 and HTS-01-19).

3. Summary of Data Needed

Data needed include all information required to validate the operational and design basis of the plate type heat exchanger design selected, all information required to develop a theoretical design basis for comparison with empirical data resulting from the prototype IHX testing performed in response to DDN HTS-01-17 and all information required to perform a verification and validation of the analytical model developed.

4. Designer's Alternatives

The designer's alternative is to select an IHX design that utilizes an existing ASME design basis, such as a shell and tube IHX.

5. Selected Design Approach and Explanation

The proposed approach is to obtain an adequate database for design, analysis and test evaluation of compact heat exchangers using the selected structural alloy and to support the development of ASME Section III Code Cases for the material and design.

6. Schedule Requirements

Final results are required by the middle of FY2011 to support design, procurement and testing of a prototype IHX modules prior to long-lead procurement of NGNP components in FY2013 and to support ASME Code Case development activities. All activities are required to support NGNP operation by the end of 2018.

7. Priority

Urgency (1-5):	1
Cost-Benefit (Low, Medium, High):	High
Uncertainty in Existing Data (Low, Medium, High):	High
Importance of New Data (Low, Medium, High):	High

8. Fallback Position and Consequences Of Non-Execution

The fallback position is to use the existing ASME design database and use an ASME Code approved heat exchanger design and material for the IHX application.

9. References

1. NGNP and Hydrogen Production Preconceptual Design Report, NGNP-01-RPT-001, *Special Study 20.3 - High Temperature Process Heat Transfer and Transport*, January 2007.

DDN HTS-01-15 CRITERIA FOR STRUCTURAL ADEQUACY OF PLATE-TYPE COMPACT HEAT EXCHANGERS AT VERY HIGH TEMPERATURES

1. Assumptions (to be confirmed by the related R&D program)

The criteria for acceptable stresses and strains and the development of acceptable safety factors are required for ASME Code Case development and to establish the operational boundaries of the IHX prototype testing activities. These criteria will be developed from a review of appropriate ASME Code documentation, discussion with appropriate ASME Code committee personnel and interaction during the development of the stress-strain model (DDN HTS-01-14).

2. Current Database Summary

The current ASME design database for shell and tube heat exchangers provides general guidance for development of appropriate stress/strain criteria for the design of plate type heat exchanger systems.

3. Summary of Data Needed

Data needed include the results from DDNs HTS-01-14 and HTS-01-17, review of prior appropriate ASME documentation and discussions with appropriate ASME committee personnel.

4. Designer's Alternatives

The designer's alternative is to select an IHX design that utilizes an existing ASME design basis, such as a shell and tube IHX.

5. Selected Design Approach and Explanation

The proposed approach is to obtain an adequate database for design, analysis and test evaluation of compact heat exchangers using the selected structural alloy and to support the development of ASME Section III Code Cases for the material and design.

6. Schedule Requirements

Final results are required by the middle of FY2011 to support design, procurement and testing of a prototype IHX module prior to long-lead procurement of NGNP components in FY2013 and to support ASME Code Case development activities. All activities are required to support NGNP operation by the end of 2018.

7. Priority

Urgency (1-5):	1
Cost-Benefit (Low, Medium, High):	High
Uncertainty in Existing Data (Low, Medium, High):	High
Importance of New Data (Low, Medium, High):	High

8. Fallback Position and Consequences Of Non-Execution

The fallback position is to use the existing ASME design database and use an existing ASME Code approved heat exchanger design and material for the IHX application.

9. References

1. NGNP and Hydrogen Production Preconceptual Design Report, NGNP-01-RPT-001, *Special Study 20.3 - High Temperature Process Heat Transfer and Transport*, January 2007.

DDN HTS-01-16 METHODS FOR PERFORMANCE MODELING OF PLATE-TYPE COMPACT HEAT EXCHANGERS

1. Assumptions (to be confirmed by the related R&D program)

Performance modeling methods are required to adequately evaluate the results of DDNs HTS-01-13 and HTS-01-14, provide guidance to testing performed in DDN HTS-01-17 and provide the basis for the discussion of modeling performed during the development of the design code case (DDN HTS-01-19).

2. Current Database Summary

The current ASME design database for shell and tube heat exchangers provides general guidance for development of appropriate performance modeling methods for the design of plate type heat exchanger systems.

3. Summary of Data Needed

Data needed include all information required to establish appropriate performance modeling methods.

4. Designer's Alternatives

The designer's alternative is to select an IHX design that utilizes an existing ASME design basis, such as a shell and tube IHX.

5. Selected Design Approach and Explanation

The proposed approach is to obtain an adequate database for design, analysis and test evaluation of compact heat exchangers using the selected structural alloy and to support the development of ASME Section III Code Cases for the material and design.

6. Schedule Requirements

Final results are required by the middle of FY2011 to support design, procurement and testing of a prototype IHX module prior to long-lead procurement of NGNP components in FY2013 and to support ASME Code Case development activities. All activities are required to support NGNP operation by the end of 2018.

7. Priority

Urgency (1-5):	1
Cost-Benefit (Low, Medium, High):	High
Uncertainty in Existing Data (Low, Medium, High):	High
Importance of New Data (Low, Medium, High):	High

8. Fallback Position and Consequences Of Non-Execution

The fallback position is to use the existing ASME design database and use an ASME Code approved heat exchanger design and material for the IHX application.

9. References

1. NGNP and Hydrogen Production Preconceptual Design Report, NGNP-01-RPT-001, *Special Study 20.3 - High Temperature Process Heat Transfer and Transport*, January 2007.

DDN HTS-01-17 IHX PERFORMANCE VERIFICATION

1. Assumptions (to be confirmed by the related R&D program)

IHX performance verification is required to empirically validate the IHX design, to resolve issues noted regarding the design and to serve as a primary input to the validation and verification process of the modeling performed. IHX performance verification includes test facility development, prototype IHX test module fabrication, IHX life prediction, IHX durability testing, IHX performance testing, IHX materials testing and interfaces with the models developed.

2. Current Database Summary

There is essentially no available database to support this DDN.

3. Summary of Data Needed

Data needed include all information required to establish the empirical basis for IHX performance, life prediction, durability and acceptability of fabricated materials in support of the ASME Design and Materials Code Cases (DDNs HTS-01-18 and HTS-01-19) and all information required to provide an empirical basis for model validation.

4. Designer's Alternatives

The designer's alternative is to select an IHX design that utilizes an existing ASME design basis, such as a shell and tube IHX.

5. Selected Design Approach and Explanation

The proposed approach is to obtain an adequate database for design, analysis and test evaluation of compact heat exchangers using the selected structural alloy and to support the development of ASME Section III Code Cases for the material and design.

6. Schedule Requirements

Final results are required in the second half of FY2011 to support design, procurement of long-lead NGNP components in FY2013 and to support ASME Code Case development activities. All activities are required to support NGNP operation by the end of 2018.

7. Priority

Urgency (1-5):	1
Cost-Benefit (Low, Medium, High):	High
Uncertainty in Existing Data (Low, Medium, High):	High
Importance of New Data (Low, Medium, High):	High

8. Fallback Position and Consequences Of Non-Execution

The fallback position is to use the existing ASME design database and use an ASME Code approved heat exchanger design and material for the IHX application.

9. References

1. NGNP and Hydrogen Production Preconceptual Design Report, NGNP-01-RPT-001, *Special Study 20.3 - High Temperature Process Heat Transfer and Transport*, January 2007.

DDN HTS-01-18 DATA SUPPORTING MATERIALS CODE CASE

1. Assumptions (to be confirmed by the related R&D program)

The IHX high-temperature primary to secondary system interface will be designed as an ASME Section III component and the selected IHX fabrication alloy for this interface (Alloy 617) will not be listed in ASME Section II for ASME Section III service in the timeframe required. Alloy 800H used in the lower temperature (<760°C) primary to secondary system interface is qualified under ASME Section III, Subsection NH and may need only extension to longer times.

2. Current Database Summary

The current mechanical and physical properties database for Alloy 617 is based primarily on multiple heats of standard ASME SB-168 plate material with a relatively large grain size (ASTM 0-3), and material of this grain size is not consistent with the needs of compact heat exchangers. The database is reasonably complete for the temperature range of room temperature to 982ºC. Standard Alloy 617 is listed in ASME Section II for application to ASME Sections I and VIII, Division 1. The ASME does not currently allow Alloy 617 for Section III applications, and it is anticipated that a Section III Code Case would need to be submitted and approved for a nuclear power application to be implemented using this material. The database also includes a draft ASME Code Case that was submitted previously for approval to the ASME. This draft material code case is not considered to be an adequate substitute for DDN HTS-01-18 and contains several technical issues that will need to be resolved.

Alloy 800H is a well-characterized material with a long history of successful service experience in applications including gas-cooled reactors. A substantial database exists for Alloy 800H for temperatures to 1000°C. It is ASME qualified under Section VIII for use to 816°C and under certain circumstances to 982°C. Section III, Subsection NH permits its use to 760°C and a joint ASME/DOE study has indicated that raising this temperature to 900°C can be technically supported.

3. Summary of Data Needed

Data needed includes all information required to draft a materials code case for Alloy 617 and to resolve issues that may occur during further discussions with the ASME during the code case approval process and during subsequent discussions with the NRC during NGNP licensing.

4. Designer's Alternatives

The designer's alternative is to select an IHX fabrication alloy listed in ASME Section II for application in ASME Section III.

5. Selected Design Approach and Explanation

The proposed approach is to obtain an adequate database for design, analysis and test evaluation of compact heat exchangers using the selected structural alloy and to support the development of ASME Section III Code Cases for the material and design.

6. Schedule Requirements

Final results are required during the first half of FY2012 to support NRC licensing discussions associated with the NGNP. All activities are required to support NGNP operation by the end of 2018.

7. Priority

Urgency (1-5):	1
Cost-Benefit (Low, Medium, High):	High
Uncertainty in Existing Data (Low, Medium, High):	High
Importance of New Data (Low, Medium, High):	High

8. Fallback Position and Consequences Of Non-Execution

The fallback position is to use the existing ASME design database and use an ASME Code approved heat exchanger design and material for the IHX application.

9. References

1. NGNP and Hydrogen Production Preconceptual Design Report, NGNP-01-RPT-001, *Special Study 20.3 - High Temperature Process Heat Transfer and Transport*, January 2007.

DDN HTS-01-19 DATA SUPPORTING DESIGN CODE CASE

1. Assumptions (to be confirmed by the related R&D program)

The IHX primary to secondary system interface will be designed as an ASME Section III component and the selected IHX compact heat exchanger design will not be included in ASME Section III in the required timeframe.

2. Current Database Summary

The current ASME design database for shell and tube heat exchangers provides general guidance for the development of a design code case for the design of plate type heat exchanger systems.

3. Summary of Data Needed

Data needed includes all information required to draft a design code case for the IHX design selected, resolve issues that may occur during further discussions with the ASME during the code case approval process and during subsequent discussions with the NRC during NGNP licensing.

4. Designer's Alternatives

The designer's alternatives are to select an IHX design listed in ASME Section VIII and use the design as the basis for a new ASME Section III Code Case or to assume that the IHX primary to secondary interface will not be designed as an ASME Section III class component.

5. Selected Design Approach and Explanation

The proposed approach is to obtain an adequate database for design, analysis and test evaluation of compact heat exchangers using the selected structural alloy and to support the development of ASME Section III Code Cases for the material and design.

6. Schedule Requirements

Final results are required during the first half of FY2012 to support NRC licensing discussions associated with the NGNP. All activities are required to support NGNP operation by the end of 2018.

7. Priority

Urgency (1-5):	1
Cost-Benefit (Low, Medium, High):	High
Uncertainty in Existing Data (Low, Medium, High):	High
Importance of New Data (Low, Medium, High):	High

8. Fallback Position and Consequences Of Non-Execution

The fallback position is to use the existing ASME design database, to use an ASME Code approved heat exchanger design and to use material for the IHX application or to proceed assuming that a Section III design is not required.

9. References

1. NGNP and Hydrogen Production Preconceptual Design Report, NGNP-01-RPT-001, *Special Study 20.3 - High Temperature Process Heat Transfer and Transport*, January 2007.

DDN HTS-01-20 INFLUENCE OF SECTION THICKNESS ON MATERIALS PROPERTIES OF ALLOY 617

1. Assumptions

The very thin material sections required for compact type IHXs will have mechanical properties equivalent to or only slightly degraded relative to those of more typical plate materials.

2. Current Database Summary

There are essentially no data available on the properties of thin sheet Alloy 617 and no existing correlations of property values versus thickness.

3. Summary of Data Needed

Data are needed to establish the variation of creep, fatigue, and creep-fatigue properties of Alloy 617 as a function of material cross-section.

4. Designer's Alternatives

The designer's alternative is to select an IHX design that does not require a thin-section material, such as a shell-and-tube IHX.

5. Selected Design Approach and Explanation

The proposed approach is to obtain an adequate database for design, analysis and test evaluation of compact heat exchangers using Alloy 617 with refined specifications and to support the development of ASME Section III Code Cases for the material and design.

6. Schedule Requirements

Results are required in early-FY2010 to support design, procurement, and testing of a prototype IHX module for verification of models. This is needed prior to long-lead procurement of NGNP components in FY2013.

7. Priority

Urgency (1-5):	1
Cost-Benefit (Low, Medium, High):	High
Uncertainty in Existing Data (Low, Medium, High):	High
Importance of New Data (Low, Medium, High):	High

8. Fallback Position

The fallback position is to select a shell and tube IHX design that would allow use of standard Alloy 617 and conventional welding processes. Non-execution of this DDN would, therefore, eliminate the option for using a compact IHX design with unacceptable performance and cost ramifications.

9. References

1. NGNP and Hydrogen Production Preconceptual Design Report, NGNP-01-RPT-001, *Special Study 20.3 - High Temperature Process Heat Transfer and Transport*, January 2007.

DDN HTS-01-21 CORROSION ALLOWANCES FOR ALLOY 617

1. Assumptions

The exposure of Alloy 617 to impure helium at high temperatures (up to 950°C) for times to at least 10 years does not compromise the structure and integrity of the material cross-section by oxide scale formation, internal oxidation, or other phenomena.

2. Current Database Summary

A significant amount of information is available relative to corrosion mechanisms for Alloy 617 in simulated gas-cooled reactor helium as a function of temperature and coolant chemistry. However, the amount of quantitative information necessary for the prediction of corrosion allowances is quite limited and often contradictory.

3. Summary of Data Needed

Data are needed to characterize the oxide scale thickness, depth of internal oxidation, and degree and depth of Cr depletion at 750°C through 1000°C on exposure to environments characteristic of both primary and secondary side He. Exposure times should range from 100 h to at least 10,000 h. These data are needed to determine “corrosion allowances” for Alloy 617. Consideration should be given to acquiring similar data on Hastelloy XR (see DDN HTS 01-31).

4. Designer’s Alternatives

The designer’s alternative is to select an IHX design that does not require a thin-section material, such as a shell-and-tube IHX.

5. Selected Design Approach and Explanation

The proposed approach is to obtain an adequate database to set corrosion allowances for Alloy 617

6. Schedule Requirements

Results are required in early-FY2010 to support design, procurement, and testing of a prototype IHX module for verification of models. This is needed prior to long-lead procurement of NGNP components in FY2013.

7. Priority

Urgency (1-5):	1
Cost-Benefit (Low, Medium, High):	High
Uncertainty in Existing Data (Low, Medium, High):	High
Importance of New Data (Low, Medium, High):	High

8. Fallback Position

The fallback position is to select a shell and tube IHX design that would allow use of thick sections. Non-execution of this DDN would, therefore, eliminate the option for using a compact IHX design with unacceptable performance and cost ramifications.

9. References

1. *IHX and HTS Conceptual Design Study*, April 2008.

DDN HTS-01-22 ESTABLISH REFERENCE SPECIFICATION FOR ALLOY 800H

1. Assumptions

The standard ASTM specification for Alloy 800H will provide a material suitable for use in the IHX.

2. Current Database Summary

Alloy 800H is a well-characterized material with a long history of successful service experience in applications including gas-cooled reactors. A substantial database exists for Alloy 800H for temperatures to 1000°C. It is ASME qualified under Section VIII for use to 816°C and under certain circumstances to 982°C. Section III, NH permits its use to 760°C and a joint ASME/DOE study has indicated that raising this temperature to 900°C is not unwarranted.

3. Summary of Data Needed

Review of Alloy 800H database.

4. Designer's Alternatives

Not applicable

5. Selected Design Approach and Explanation

The proposed approach is to accept the standard specification for Alloy 800H.

6. Schedule Requirements

Results are required in early-FY2010 to support design, procurement, and testing of a prototype IHX module for verification of models. This is needed prior to long-lead procurement of NGNP components in FY2013.

7. Priority

Urgency (1-5):	1
Cost-Benefit (Low, Medium, High):	High
Uncertainty in Existing Data (Low, Medium, High):	High
Importance of New Data (Low, Medium, High):	High

8. Fallback Position

Revise ASTM specification for Alloy 800H.

9. References

1. Swindeman, R. W., et.al., *A Report on the Review of Databases, Data Analysis Procedures, and Verification of Minimum Yield and Ultimate Strengths for Alloy 800H in ASME Section III, Subsection NH*, March 2007.
2. Swindeman, R. W., et.al., *Creep-Rupture Data Sources, Data Analysis Procedures, and the Estimation of Strength for Alloy 800H at 750^{o}C and Above*, March 2007.

DDN HTS-01-23 SUPPLEMENTAL HIGH TEMPERATURE MECHANICAL PROPERTIES OF ALLOY 800H

1. Assumptions

The existing high temperature mechanical properties of Alloy 800H are sufficient to provide for a design of an IHX operating at <760°C. Exceptions to this are addressed in DDNs HTS-01-24 through HTS-01-29.

2. Current Database Summary

See References and ASME Section III, Subsection NH.

3. Summary of Data Needed

No basic properties required.

4. Designer's Alternatives

Develop new database.

5. Selected Design Approach and Explanation

The proposed approach is to accept the current database for Alloy 800H.

6. Schedule Requirements

Results are required in early-FY2010 to support design, procurement, and testing of a prototype IHX module for verification of models. This is needed prior to long-lead procurement of NGNP components in FY2013.

7. Priority

Urgency (1-5):	1
Cost-Benefit (Low, Medium, High):	High
Uncertainty in Existing Data (Low, Medium, High):	High
Importance of New Data (Low, Medium, High):	High

8. Fallback Position

None.

9. References

1. Swindeman, R. W., et.al., *A Report on the Review of Databases, Data Analysis Procedures, and Verification of Minimum Yield and Ultimate Strengths for Alloy 800H in ASME Section III, Subsection NH*, March 2007.
2. Swindeman, R. W., et.al., *Creep-Rupture Data Sources, Data Analysis Procedures, and the Estimation of Strength for Alloy 800H at 750^{o}C and Above*, March 2007.

DDN HTS-01--24 EFFECTS OF JOINING TECHNIQUES ON THE PROPERTIES OF ALLOY 800H

1. Assumptions

Alloy 800H joined by conventional welding processes, by diffusion bonding, and by brazing will have properties suitable to permit safe and successful operation of an IHX of compact design.

2. Current Database Summary

The current database for Alloy 800H includes extensive information on conventional welding processes. However, the existing database contains very little information on thin sheet diffusion bonding or brazing, which are essential for the fabrication of PCHE and plate-fin compact heat exchangers, respectively.

3. Summary of Data Needed

Data are needed on the effects of brazing and diffusion bonding of thin sheet materials on all standard mechanical properties (tensile, creep, fatigue, and fracture toughness) at temperatures up to 850°C.

4. Designer's Alternatives

Assume the risk of not confirming the DDN Assumption.

5. Selected Design Approach and Explanation

Obtain the data needed described above.

6. Schedule Requirements

Results are required in early-FY2010 to support design, procurement, and testing of a prototype IHX module for verification of models. This is needed prior to long-lead procurement of NGNP components in FY2013.

7. Priority

Urgency (1-5):	1
Cost-Benefit (Low, Medium, High):	High
Uncertainty in Existing Data (Low, Medium, High):	High
Importance of New Data (Low, Medium, High):	High

8. Fallback Position

Accept the state of knowledge relative to welding effects and design for a shell-and-tube IHX.

9. References

1. *IHX and HTS Conceptual Design Study*, April 2008.

DDN-HTS-25 EFFECTS OF AGING ON THE PROPERTIES OF ALLOY 800H

1. Assumptions

Thermal aging will not significantly degrade the properties of Alloy 800H in IHX service exposures at up to 760°C for full reactor lifetime.

2. Current Database Summary

The stability of properties of Alloy 800H during long-term service in industrial processes and in gas-cooled reactors has been demonstrated by experience. Additionally, the effects of aging and exposures to gas-cooled reactor environments have been studied extensively in R&D programs. Results under conditions expected in the low temperature portion of the IHX are encouraging.

3. Summary of Data Needed

New data are not likely to be needed but this should be confirmed by documentation of existing service experience and R&D results.

4. Designer's Alternatives

Conduct new studies on aging effects.

5. Selected Design Approach and Explanation

Accept the existing database.

6. Schedule Requirements

Results are required in early-FY2010 to support design, procurement, and testing of a prototype IHX module for verification of models. This is needed prior to long-lead procurement of NGNP components in FY2013.

7. Priority

Urgency (1-5):	1
Cost-Benefit (Low, Medium, High):	High
Uncertainty in Existing Data (Low, Medium, High):	High
Importance of New Data (Low, Medium, High):	High

8. Fallback Position

Not applicable.

9. References

1. Swindeman, R. W., et.al., *A Report on the Review of Databases, Data Analysis Procedures, and Verification of Minimum Yield and Ultimate Strengths for Alloy 800H in ASME Section III, Subsection NH*, March 2007.
2. Swindeman, R. W., et.al., *Creep-Rupture Data Sources, Data Analysis Procedures, and the Estimation of Strength for Alloy 800H at 750°C and Above*, March 2007.

DDN HTS-01-26 EFFECTS OF EXPOSURE IN IMPURE HELIUM ON ALLOY 800H PROPERTIES

1. Assumptions

Alloy 800H can be used at very high temperatures in a slightly impure helium environment containing CO, CO_2, H_2, H_2O and O_2 at up to 760ºC for full reactor lifetime without unacceptable degradation of mechanical properties or microstructure.

2. Current Database Summary

The current database for Alloy 800H contains considerable information on the corrosion, microstructural stability, and consequent mechanical property changes as a function of time, temperature and environmental conditions. The database contains little or no information on the effects of long-term environmental exposure at very high temperature on welded, brazed, or diffusion bonded specimens. Aging and environment effects on Alloy 800H are closely related.

3. Summary of Data Needed

Data needed include selected mechanical properties (yield, tensile strength and elongation; fatigue and creep strength; fracture toughness, etc.) following environmental exposure at temperatures up to 850ºC on welded, brazed, and diffusion bonded test specimens.

4. Designer's Alternatives

Accept the risk of not confirming the DDN Assumption.

5. Selected Design Approach and Explanation

Obtain environmental effects data on welded, brazed, and diffusion bonded Alloy 800H.

6. Schedule Requirements

Results are required by the end of FY2010 to support design, procurement, and testing of a prototype IHX module for verification of models. This must be done prior to long-lead procurement of NGNP components in FY2013.

7. Priority

Urgency (1-5):	1
Cost-Benefit (Low, Medium, High):	High
Uncertainty in Existing Data (Low, Medium, High):	High
Importance of New Data (Low, Medium, High):	High

8. Fallback Position

The fallback position is to select a shell and tube IHX design that would allow use of conventional welding processes. Non-execution of this DDN would, therefore, eliminate the option for using a compact IHX design with unacceptable performance and cost ramifications.

9. References

1. *IHX and HTS Conceptual Design Study*, April 2008.

DDN HTS-01-27 INFLUENCE OF GRAIN SIZE ON MATERIAL PROPERTIES OF ALLOY 800H

1. Assumptions

Alloy 800H with fine grain size will have acceptable mechanical properties at temperatures to 800^{o}C for long periods of time and reasonably fine grain size can be maintained following joining and high temperature long-term exposure.

2. Current Database Summary

There is little if any information available on the properties of Alloy 800H with grain size smaller than that given by ASTM 5 (248 grains/mm^2).

3. Summary of Data Needed

Obtain property information on Alloy 800H in the grain size range ASTM 5 to 8. This could be done on one or more heats of Alloy 800H acquired specifically for NGNP or on existing large-grained materials processed to achieve a smaller grain size.

4. Designer's Alternatives

Accept the risk of not confirming the DDN Assumption and design with standard Alloy 800H properties.

5. Selected Design Approach and Explanation

Obtain creep and fatigue property data for fine-grained Alloy 800H.

6. Schedule Requirements

Results are required by the end of FY2010 to support design, procurement, and testing of a prototype IHX module for verification of models. This must be done prior to long-lead procurement of NGNP components in FY2013.

7. Priority

Urgency (1-5):	1
Cost-Benefit (Low, Medium, High):	High
Uncertainty in Existing Data (Low, Medium, High):	High
Importance of New Data (Low, Medium, High):	High

8. Fallback Position

The fallback position is to select a shell and tube IHX design that would allow use of large grained material. Non-execution of this DDN would, therefore, eliminate the option for using a compact IHX design with unacceptable performance and cost ramifications.

9. References

1. *IHX and HTS Conceptual Design Study*, April 2008.

DDN HTS-01-28 INFLUENCE OF SECTION THICKNESS ON MATERIAL PROPERTIES OF ALLOY 800H

1. Assumptions

Very thin material sections of Alloy 800H required for compact type IHXs will have mechanical properties equivalent to or only slightly degraded relative to those of plate materials with more typical thicknesses.

2. Current Database Summary

There are no data available on the properties of thin sheet Alloy 800H and no existing correlations of property values versus thickness.

3. Summary of Data Needed

Data are needed to establish the variation of properties of Alloy 800H as a function of material thickness.

4. Designer's Alternatives

Accept the risk of not confirming the DDN Assumption and design with standard Alloy 800H properties.

5. Selected Design Approach and Explanation

Obtain creep and fatigue property data for thin sheet Alloy 800H.

6. Schedule Requirements

Results are required by the end of FY2010 to support design, procurement, and testing of a prototype IHX module for verification of models. This must be done prior to long-lead procurement of NGNP components in FY2013.

7. Priority

Urgency (1-5):	1
Cost-Benefit (Low, Medium, High):	High
Uncertainty in Existing Data (Low, Medium, High):	High
Importance of New Data (Low, Medium, High):	High

8. Fallback Position

The fallback position is to select a shell and tube IHX design that would allow use of heavy section materials. Non-execution of this DDN would, therefore, eliminate the option for using a compact IHX design with unacceptable performance and cost ramifications.

9. References

1. *IHX and HTS Conceptual Design Study*, April 2008.

DDN HTS-01-29 CORROSION ALLOWANCES FOR ALLOY 800H

1. Assumptions

The exposure of Alloy 800H to impure helium at high temperatures for full reactor lifetime does not compromise the structure and integrity of the material cross-section by oxide scale formation, internal oxidation, or other phenomena.

2. Current Database Summary

A significant amount of information is available relative to corrosion mechanisms for Alloy 800H in simulated gas-cooled reactor helium as a function of temperature and coolant chemistry. However, the amount of quantitative information necessary for the prediction of corrosion allowances is quite limited and often contradictory.

3. Summary of Data Needed

Data are needed to characterize the oxide scale thickness, depth of internal oxidation, and degree and depth of Cr depletion at 650°C through 850°C on exposure to environments characteristic of both primary and secondary side He. Exposure times should range from 100 h to at least 10,000 h. These data are needed to determine "corrosion allowances" for Alloy 800H.

4. Designer's Alternatives

Accept the risk of not confirming the DDN Assumption and design without corrosion allowances.

5. Selected Design Approach and Explanation

Determine corrosion allowances for Alloy 800H.

6. Schedule Requirements

Results are required in early-FY2010 to support design, procurement, and testing of a prototype IHX module for verification of models. This is needed prior to long-lead procurement of NGNP components in FY2013.

7. Priority

Urgency (1-5):	1
Cost-Benefit (Low, Medium, High):	High
Uncertainty in Existing Data (Low, Medium, High):	High
Importance of New Data (Low, Medium, High):	High

8. Fallback Position

The fallback position is to select a shell and tube IHX design that would allow use of heavy section materials without significant concern about corrosion. Non-execution of this DDN would, therefore, eliminate the option for using a compact IHX design with unacceptable performance and cost ramifications.

9. References

1. *IHX and HTS Conceptual Design Study*, April 2008.

DDN HTS-01-30 BRAZING AND DIFFUSION BONDING PROCESSES FOR ALLOY 617 AND ALLOY 800H

1. Assumptions

Thin sections of Alloy 617 and Alloy 800H can be brazed and/or diffusion bonded to produce structurally sound joints in compact heat exchangers.

2. Current Database Summary

There is very little information or data available on materials and techniques for brazing and diffusion bonding thin sections of Alloy 617 and Alloy 800H and most of this is likely company proprietary. Also, information on the strength and structural integrity of such joints is lacking.

3. Summary of Data Needed

Data and information needed include determination and documentation of suitable braze materials and conditions and diffusion bonding techniques for joining of thin sections of Alloy 617 and Alloy 800H. Assessment of the structural integrity of these joints by microscopic examination and mechanical testing is also needed.

4. Designer's Alternatives

Use properties of base material and accept the risk of not confirming the Assumption.

5. Selected Design Approach and Explanation

Demonstrate joining by brazing and diffusion bonding.

6. Schedule Requirements

Results are required in early-FY2010 to support design, procurement, and testing of a prototype IHX module for verification of models. This is needed prior to long-lead procurement of NGNP components in FY2013.

7. Priority

Urgency (1-5):	1
Cost-Benefit (Low, Medium, High):	High
Uncertainty in Existing Data (Low, Medium, High):	High
Importance of New Data (Low, Medium, High):	High

8. Fallback Position

The fallback position is to select a shell and tube IHX design that would allow use of standard welding practice. Non-execution of this DDN would, therefore, eliminate the option for using a compact IHX design with unacceptable performance and cost ramifications.

9. References

1. *IHX and HTS Conceptual Design Study*, April 2008.
2. *IHX and HTS Conceptual Design Study*, April 2008, Appendix 1.

DDN HTS-01-31 READINESS ASSESSMENT FOR HASTELLOY XR AS AN IHX MATERIAL

1. Assumptions

Hastelloy XR would be an acceptable substitute for Alloy 617 and/or Alloy 800H for the construction of a compact heat exchanger (IHX).

2. Current Database Summary

The database for Hastelloy XR is extensive in Japan for temperatures up to 1000°C. The alloy is code approved in Japan and has been used for short periods of time at temperatures to 950°C in the prototype high-temperature gas-cooled reactor at JAERI. Its high temperature strength is inferior to that of Alloy 617, but superior to that of Alloy 800H, and its corrosion resistance appears much superior to both Alloy 617 and Alloy 800H.

3. Summary of Data/Information/Actions Needed

The Japanese database for Hastelloy XR needs to be acquired through negotiations with Japanese gas-cooled reactor programs. Additional corrosion data should be acquired through DDN HTS-01-21.

4. Designer's Alternatives

Use Alloy 617 and Alloy 800H.

5. Selected Design Approach and Explanation

Conduct readiness review for Hastelloy XR.

6. Schedule Requirements

Results are required in early-FY2010 to support design, procurement, and testing of a prototype IHX module for verification of models. This is needed prior to long-lead procurement of NGNP components in FY2013.

7. Priority

Urgency (1-5):	1
Cost-Benefit (Low, Medium, High):	High
Uncertainty in Existing Data (Low, Medium, High):	High
Importance of New Data (Low, Medium, High):	High

8. Fallback Position

Not applicable.

9. References

1. *IHX and HTS Conceptual Design Study*, April 2008.